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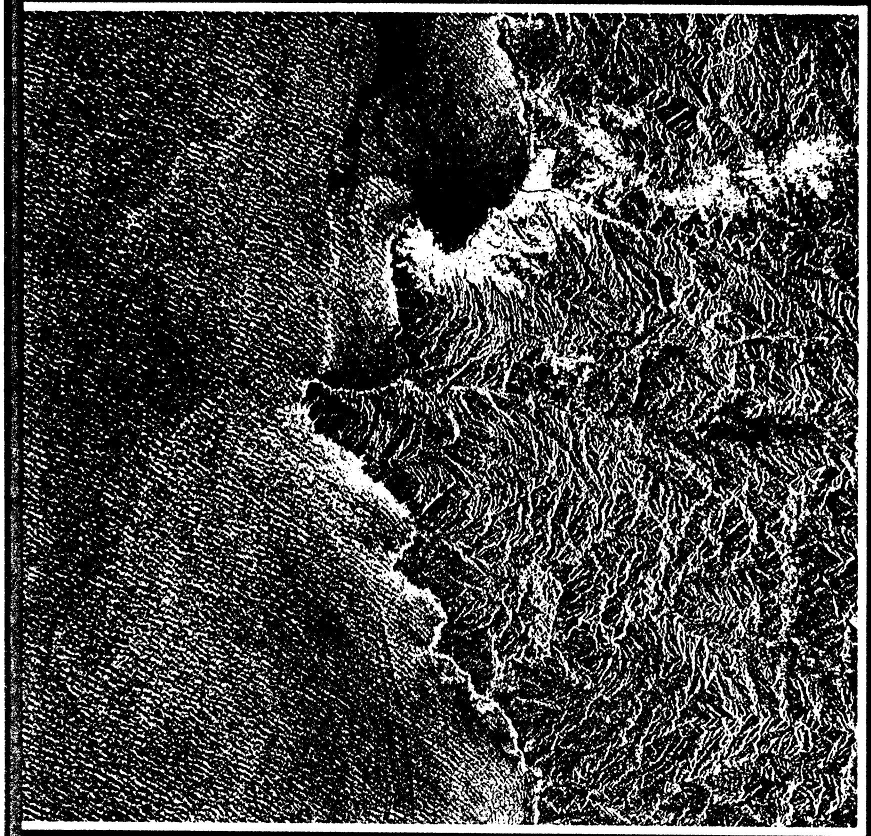

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ANALYSIS OF FLOODING DYNAMICS IN THE PANTANAL, USING TIME SERIES OF ERS-1 SAR IMAGERY

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Abstract

The Pantanal is a wetland ecosystem with a seasonal cycle of flooding and drydown. This creates a number of landscapes that are heterogeneous spatially and temporally. These include freshwater and saline lakes, periodically inundated grasslands and forested sections that are highly heterogeneous in spatial arrangement and in response to inundation. This region is well suited to perform spatio-temporal analysis of land cover dynamics from SAR image time series, since land cover types can exhibit great contrasts in backscattering. In this study, we use seven ERS-1 SAR images from December 1992 to November 1993. This period includes both seasonal inundation followed by a significant climatic drought that transformed the spatial structure of backscattering across the landscape. Lacunarity analysis of the SAR image series captures the spatio-temporal rearranging and illustrates how complex land cover change can be quantified within a predictive framework.

1. Introduction and Objectives

The initial objective of this project was to investigate the feasibility of using spaceborne SAR to monitor the flooding within the *Pantanal Matogrossense*, the largest wetland on the planet. The first analysis of ERS-1 SAR data processed by INPE, indicated that several environmental factors in the Pantanal interact to create a significant challenge to flood mapping. Specifically, the region's reduced declivity (2-5 cm/km), the well-drained sandy soils, and the spatial heterogeneity of minor local topographic variations (1-3 m) that control the vegetation composition and the seasonality of inundation, all combine to generate landscapes that are characterized by extreme spatio-temporal heterogeneity (Henebry & Kux 1995b).
Given this heterogeneity, change detection and quantification became difficult tasks, and we faced the following questions: 1. What is an appropriate baseline? 2. What constitutes an acceptable range of radiometric variation within an area? 3. How to measure spatial heterogeneity through time? We concluded that it was imperative to develop an approach to measure heterogeneity in space and time in order to provide robust dynamic baseline behaviors for operational environmental monitoring using SAR, whether in the Pantanal or any remote region of ecological and economic interest, such as e.g. the floodplains of Amazonia.

One of the most interesting regions within the Pantanal is the southern section of the Rio Taquarí floodplain, called Nhecolândia. It is an area of high radiometric contrast due to a landscape full of perennial and ephemeral lakes, corridors of forests, and sections of periodically inundated grasslands. Furthermore, floating canopies of aquatic macrophytes emerge following inundation and change the surface roughness of the water to enhance microwave backscattering.

2. Detailed description of experiment

Spatial analyses of SAR data are hindered by the high frequency noise of speckle. There is a need for a robust procedure for SAR scene spatial analysis. We developed a new approach, lacunarity analysis, during Dr. Henebry's Fulbright Scholar visit to INPE during 1993-94.

Lacunarity describes the complex intermingling of the shape and distribution of gaps within an image: a highly *lacunar* image exhibits gaps distributed across a broad range of sizes (Henebry and Kux 1995a; Plotnick et al. 1993). Lacunarity is an aspect of fractal geometry: lacunarity (L) is the multiplicative prefactor in the general power-law formula of which the fractal dimension is the exponent, $F(x)= Lx^{(D-E)}$. As a texture measure, lacunarity quantifies the deviation of a geometric object (e.g., shape, pattern, fractal) from translational invariance and thus is well-suited to analysis of natural scenes.

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Lacunarity can be estimated by a simple index, λ1, which is sensitive to observation scale, as is expected from a fractal measure. Indeed, the index's descriptive power is revealed only when it is observed as a function of window size *w*, hence we use λ(*w*). The image value of λ(*w*) occurs when the window size equals the spatial resolution of the image, i.e. when the variance is zero. Calculation details can be found in Plotnick et al. (1993) with significant modifications for SAR imagery in Kux and Henebry (1994b); Henebry and Kux (1995a and 1996).

Lacunarity indices use multiscale windowing to measure the scale dependency of spatial heterogeneity and anisotropy in binary maps in terms of departures from translational and rotational invariance (Plotnick et al. 1993; Henebry and Kux 1995a; Henebry and Kux 1996). The indices are sensitive to the map density and local aggregation. Higher lacunarity indicates a more sparse, more clumped distribution within the map. Random maps show little persistent spatial structure under multiscale windowing and thus exhibit low lacunarity scores (Fig.1). Conversely maps containing larger aggregates maintain high lacunarity scores until the extent of the sampling window exceeds the extent of the aggregates. Thus for spatio-temporal analyses it is useful to track lacunarity using a constant window size. Anisotropy can be estimated by the ratio of lacunarity indices obtained from rectangular windows with extreme but complementary shapes, e.g., *w (1j)* and *w(1j)* (Fig. 5) (Kux and Henebry 1994b).

Although the definition of lacunarity is restricted to binary data, gray-scale (ordinal or interval) data can be analyzed by deriving a series of binary images based on quantiles of the image histogram. We construct four binary images from each SAR image corresponding to the quartiles of the histogram. For example, in the first quartile image (Q1) pixels having gray levels between the minimum and the 25th percentile are mapped to white and the remaining pixels are mapped to black. The Q1 image thus illustrates the spatial distribution of the regions in the scene that have the least backscatter; similarly, the Q4 image captures the arrangement of the pixels with the greatest backscatter. The decay of lacunarity as a function of window size, characterizes scale-dependency of spatial non-stationarity in binary image. Changes in the spatial arrangement of backscattering translate into changes in the lacunarity function; thus lacunarity analysis is useful for characterization of natural spatio-temporal variability within a scene as well as change detection. Finally, lacunarity analysis can discriminate between the texture of speckle noise and the texture intrinsic to the scene. Speckle noise is manifested as a spatially random texture and the lacunarity analysis of a spatially random binary process exhibits a characteristic rapid decay to the minimum value as window size increases; whereas, scene texture will exhibit a more complicated decay, if the sensor is indeed well-suited to reveal scene texture.

Presently we are working with an ERS-1 SAR image time series of seven dates (Table 1). This image series covers one inundation cycle during 1992-93, which included a significant drought event during the later part of the cycle (Fig. 2). We have analyzed these data in various ways, resulting in several publications and presentations at scientific symposia. Our results are outlined in section 3 below.

3. Results of the experiment

Initially we had access to only three scenes from Nhecolândia: 12.12.92, 20.02.93 and 01.05.93. On these data we were able to develop and refine the procedures for lacunarity analysis. Specifically the following was shown:

(1) lacunarity was more sensitive to changes in spatial structure and texture than the typical SAR texture based on the gray level co-occurrence matrix (Kux and Henebry 1994a);

(2) lacunarity could measure changing scene anisotropy during flooding (Fig.3) (Kux and Henebry 1994b);

(3) lacunarity, coupled with quartile slicing, could: (a) distinguish relevant scene texture from speckle noise and (b) be used to relate changes in image structure to actual changes in the landscape (Fig. 4) (Henebry and Kux 1995a).

Upon acquiring four additional SAR scenes that complete the 1992-93 inundation cycle, we have been able to explore more fully the spatio-temporal heterogeneity of the Nhecolândia region. Within each of the seven scenes we selected several representative landscapes for detailed analysis using lacunarity indices based on the first (Q1) and fourth (Q4) quartile binary images derived from each date. To facilitate comparison of shifts in spatial arrangement, we mapped these indices into a common metric space (Fig. 4). Some of these results are shown in Figures 5 to 7 and appeared in Henebry and Kux (1996). The plots appear to show in each case a definite perturbation to a quasi-periodic trajectory in the metric space. We suspect that the proximate cause of the perturbation is the significant drought that the Pantanal experienced in the latter half of 1993. This is an exciting result, since it illustrates the utility of lacunarity analysis of multi-date SAR image series for environmental change detection and quantification.

In landscapes such as those from the Pantanal the use of only Q1 and Q4 binary data has shown to be the most efficient. In earlier work (Henebry and Kux 1995a; Kux and Henebry 1994b), we saw that most of the spatial heterogeneity was located in Q1 and Q4, corresponding to the lowest and highest backscattering values, while the middle 50 percent of the histogram was dominated by spatially random noise. This was again the case for each landscape examined. Together Q1 and Q4, although comprising 50 percent of the pixels, accounted for 72 to 91 percent of the total lacunarity. The partitioning of anisotropy, however, was a different matter. There was no significant difference between quartiles at a single date, although there was significant variation in anisotropy over the course of the image series (Henebry and Kux 1996).

We have devised a further demonstration of the high information content of the extreme quartiles - a comparison of image segmentations, one based on a principal components analysis (PCA) of the seven date full (16-bit) image series, versus the other based on a PCA of Q1 and Q4 images, derived from each of the seven dates. The first four principal components (PCs) from each PCA were submitted to an unsupervised (ISODATA) classification to 5 classes. A 3x3 majority filter was then applied twice and two classes were merged to bring the total number of classes to three.

As can be seen in Figure 8, the segmentations are quite comparable. Black represents perennially wet areas. Gray denotes areas not flooded, such as forested regions on locally higher terrain. White represents areas of significant water level change, whether inundated grasslands or exposed shoreline from lake drydown. It is important to note that 112 data bits per pixel (16 bits x 7 dates) were submitted to PCA to derive the image on the left; whereas, only 14 bits per pixel (1 bit x 7 dates x 2 quartiles) were submitted to PCA to derive the image on the right !

While these results are impressive, segmentation to only three classes is probably not optimal. Ground level observations are difficult to obtain in this remote and geomorphologically very dynamic region. We are, however, pursuing further segmentation and classification of these scenes using additional classes.

4. Discussion and Conclusions

This study has been quite successful and fruitful in terms of: (1) development of tools for SAR spatial analysis, (2) documentation of Pantanal's dynamics, (3) assessment of multi-date SAR data for land cover monitoring in areas susceptible to flooding. We believe there is significant potential to transfer the approaches developed here to a project related to the delineation of the Rio Amazonas floodplains, e.g. the *Várzea/Terra Firme* boundary.

The project outcomes represents a refinement rather than a divergence of the original objectives: the extreme radiometric seasonality coupled with extreme spatial heterogeneity required that significant resources be devoted to quantifying the development of spatial pattern through time. Furthermore, the reduced declivity of the landscape and its dynamic character mean that there are no terrain models or persistent landmarks to aid image navigation and georeferencing. These constraints required the development of image analysis procedures that were atypical but quite appropriate to the local situation.

This study is part of an ERS-1/2 supported project (AO2.BR105) during which we will add to our SAR image time in order to (1) refine our analytical techniques, (2) develop a library of spatio-temporal land cover signatures, (3) improve the segmentation and classification of the scenes, (4) link with other investigators working at coarser spatial resolutions, and (5) work with a complementary RADARSAT project (PI: J. Melack, UCSB) of which Henebry is a Co-investigator.

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Table 1: ERS1-SAR data from track 210 and frame 3987

Acquisition Data	Orbit Number	Center Latitude	Center Longitude
12.12.92	7369	S 19°12'04"	E 304°02'06"
20.02.93	8371	S 19°12'40"	E 304°01'26"
01.05.93	9373	S 19°15'00"	E 304°01'19"
05.06.93	9874	S 19°11'42"	E 304°02'10"
14.08.93	10876	S 19°11'38"	E 304°01'52"
18.09.93	11377	S 19°12'14"	E 304°01'19"
27.11.93	12379	S 19°11'56"	E 304°01'55"

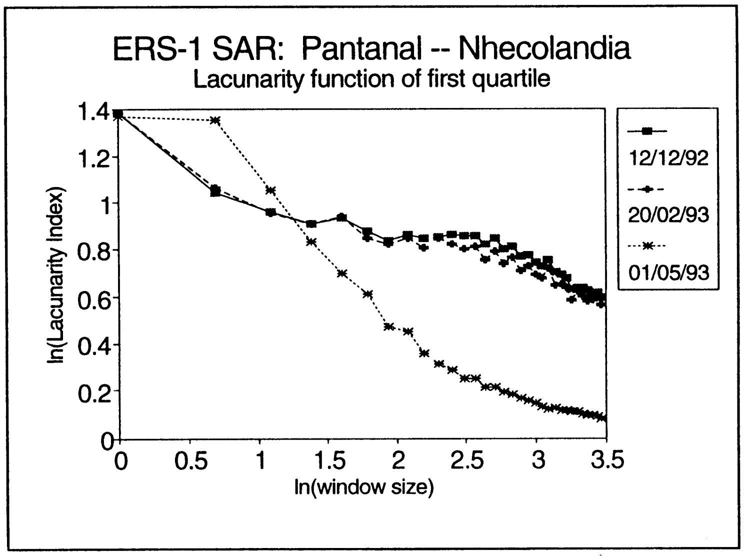


Figure 1: Rapid decay of lacunarity indicates quasi-random spatial arrangement; decay is slower when large aggregates of pixels generate more spatial heterogeneity.

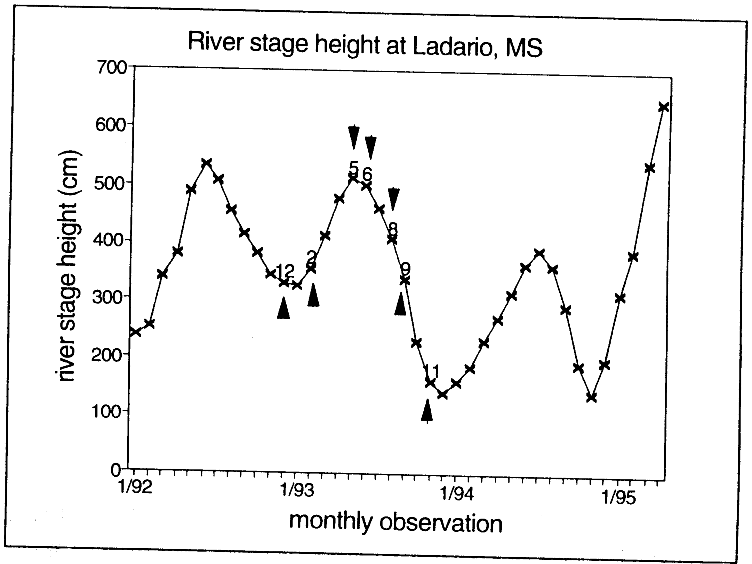


Figure 2: River stage height at Ladario, Mato Grosso do Sul. Arrows and numbers indicate month of acquisition for ERS-1 SAR data used in the study.

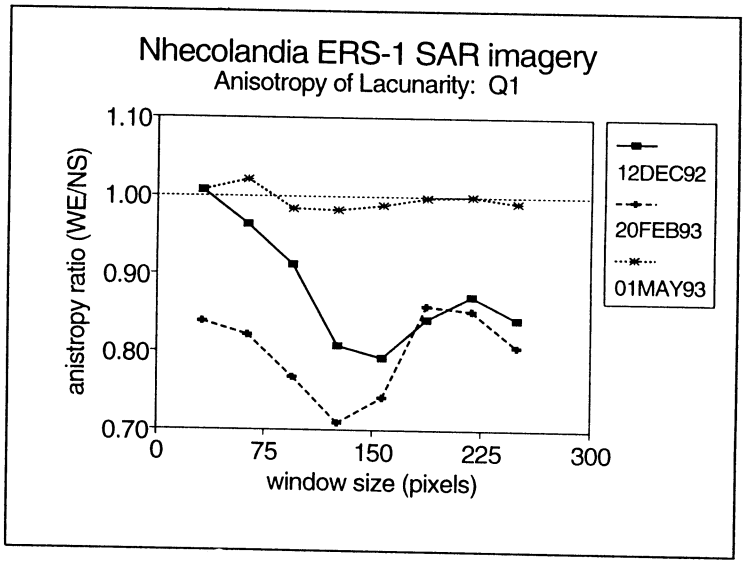


Figure 3: Lacunarity is also sensitive to the anisotropy of pixel arrangements. The north-south orientation evident DEC and FEB is lost in MAY due to flooding.

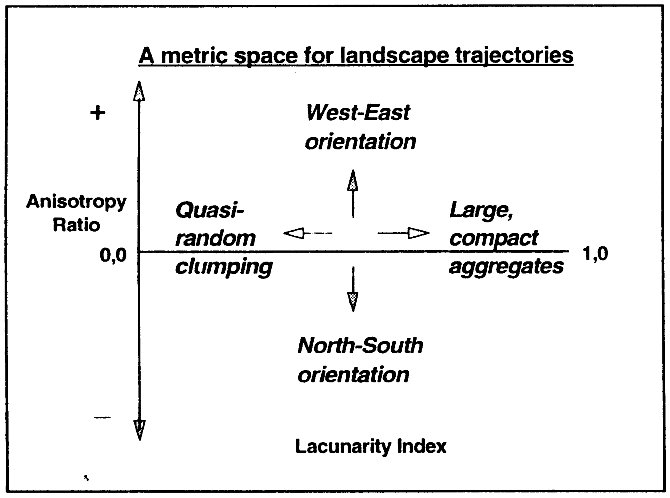


Figure 4: A metric space for landscape trajectories derived from SAR image time series. Normalized lacunarity forms the x-axis and anisotropy ratio of lacunarity forms the y-axis.

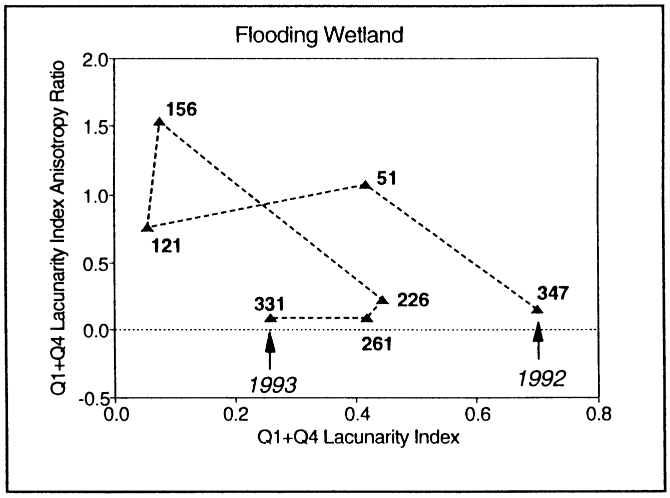


Figure 5: Landscape trajectory of a flooding wetland . Note the disparity between trajectory endpoints, attributable to a drought.

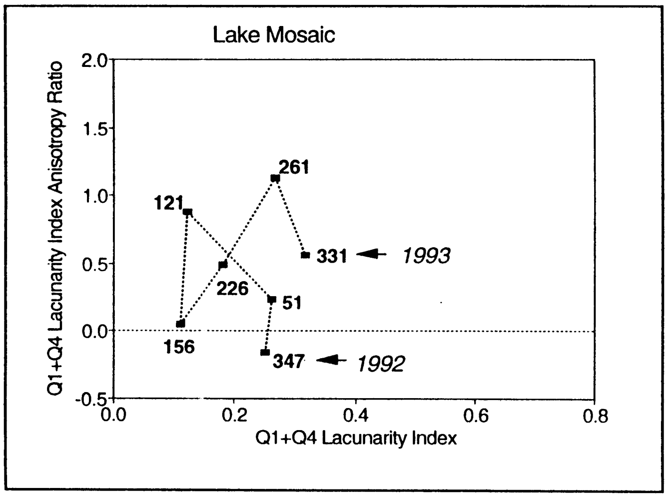


Figure 6: Landscape trajectory for a lake mosaic. Note the attenuation of anisotropy as a result of the drought in the austral winter of 1993.

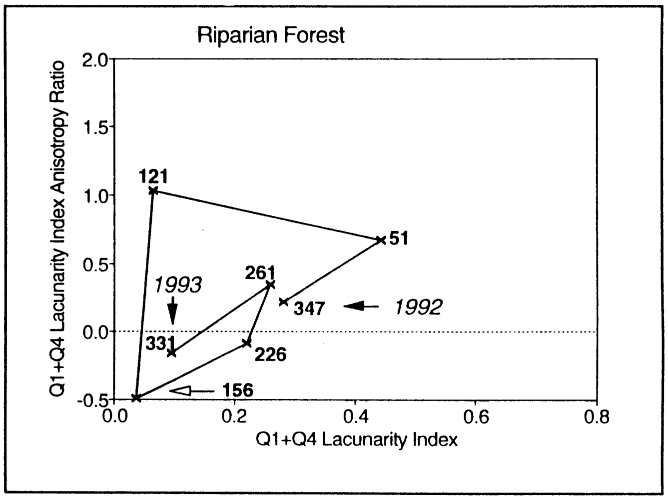
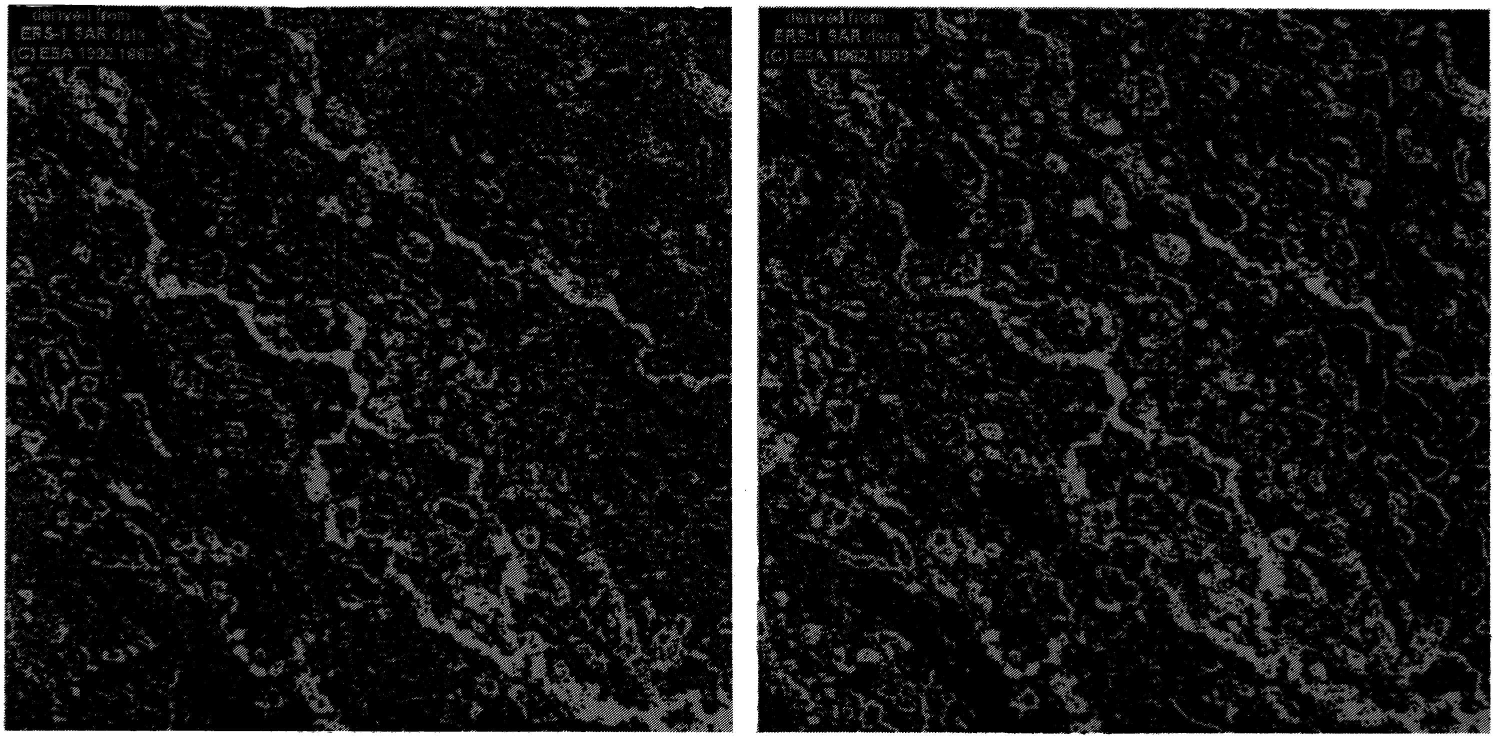


Figure 7: Landscape trajectory for a riparian forest. Note the lack of significant spatial structure (low values on both axes) at DOY 331.



Classification based on PCA of full image series

Classification based on PCA of Q1 + Q4 series

Figure 8