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**INVESTIGATIONS AT CATIE ON THE POTENTIAL OF HIGH-  
RESOLUTION RADAR IMAGES FOR MONITORING OF  
AGRICULTURE IN CENTRAL AMERICA**

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# INVESTIGATIONS AT CATIE ON THE POTENTIAL OF HIGH-RESOLUTION RADAR IMAGES FOR MONITORING OF AGRICULTURE IN CENTRAL AMERICA

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## ABSTRACT

*This article reviews the investigations that are presently carried on at the Tropical Agriculture Research and Training Centro (CATIE) on the use of Synthetic Aperture Radar (SAR) for agricultural purposes. The major themes that are being studied are a) radiometric corrections to compensate the effects of topography, b) the ability of SAR images to distinguish crops and land use types, bare soil from developed crops as well as different growing stages in sugar cane, c) their potential for the mapping of sweet banana and plantain banana plantations, as well as for the diagnosis and mapping of Black Sigatoka infection in these latter crops.*

## INTRODUCTION

CATIE, a regional institution working on matters related to natural resources in the American Tropics, has played a leading role for the development of Remote Sensing and Geographic Information Systems in Central America. Since the operation of image processing capacity in 1986, CATIE has conducted numerous projects based on the use of optical remote sensing applied to agriculture and land use mapping in Guatemala, El Salvador, Honduras, Nicaragua and Costa Rica. Nevertheless, researchers at CATIE were rapidly faced with the difficulties in obtaining reasonably cloud-free optical satellite images of most parts of the region. A study conducted by Maraux and Garcia using long time-series of GOES images (Maraux and Garcia, 1990) showed that for SPOT and Landsat the probabilities involved are indeed very low, in particular for Costa Rica and Panama. Research oriented towards radar imagery at CATIE began in 1992 to study the images that would result from the South American Radar Experiment (SAREX) program and Proyecto Radar Costa Rica/Canadá (Elizondo *et al.*, 1993).

Most of the studies on radar imagery carried out in tropical environments have focused on geology or on forest investigation. On the other hand, most of

the research on the use of radar imagery for agricultural purposes has been conducted in temperate regions where not only the crops are different, but the fields are usually large, flat, uniform and have a regular shape, as can be seen in Wooding (1988) and Brown *et al.* (1993). There is therefore not much known about the potential of SAR images for the inventory and monitoring of tropical crops. The lack of this type of research in Central America can be easily understood, since the combination of microparcelation and a pronounced topography significantly complicates the matter. In addition topography causes particular geometrical distortions in radar images which must be corrected in order to map features and measure areas. Since radar is an active system, topography also causes foreshortening, layover, shadows, and important radiometric modulations, with the slopes facing the antenna appearing very bright and the ones facing away appearing darker, which impede visual interpretation of vegetation as well as any quantitative analysis. In all three areas covered by the article, the presented results are preliminary and the research is ongoing.

## RADAR IMAGES

The investigations oriented towards radiometric corrections (Leclerc *et al.*, 1993) and general crop discrimination (Beaulieu *et al.*, 1993) were conducted using flight lines 8.1, 8.2 and 8.3 of the Costa Rican series, whereas the investigation on sweet banana and plantain banana (Pigeonnat, 1993, Pigeonnat *et al.*, 1993) has been conducted with flight lines number 2.1 and 2.2. These images were acquired by the Canada Centre for Remote Sensing's (CCRS) C-SAR sensor aboard the CONVAIR-580 aircraft. They are seven-look images that have been acquired in two modes of polarization, Horizontal emitted-Horizontal Received (HH), and Vertical emitted-Vertical received (VV). Their digital Number (DN), which has been recorded in an 8-bit format, is proportional to the square root of the

received radar power. Their slant range resolution is 6m in the range and azimuth directions, with a pixel size of 4 m in the range direction and 4.31 m in the azimuth direction.

The flight lines of series number 8 are the only Costa Rican images which were acquired in narrow mode with depression angles ranging from 14° to 45° and an approximate swath width of 18 km. They were part of the flight lines that were funded by the Canada Centre for Remote Sensing (CCRS), as a complement to the SAREX project. They cover a 2700 km<sup>2</sup> region in the central volcanic cordillera of Costa Rica where the major crops are vegetable crops, pasture, coffee and sugar cane. They were acquired April 27<sup>th</sup> of 1992.

Flight lines of series number 2 were acquired April 21<sup>th</sup> in Nadir mode, with depression angles varying from 16° to 90°. They cover an important part of the Atlantic coast of Costa Rica.

### RADIOMETRIC CORRECTION OF TOPOGRAPHIC EFFECTS

Although quite a few image processing packages allow the precise georectification of radar images with the help of a Digital Elevation Model (DEM), we do not know of a commercial package offering radiometric corrections of the effects of topography for these images. Through an agreement with PCI Inc., Canada, two full versions of the EASI/PACE image processing system were installed in our laboratory, which brought us a strong platform to study radar imagery. A simple methodology for the calculation of the local incidence angle of radar radiation and the radiometric correction of topographic effects was developed.

The calculation of local incidence angle is conducted through the geometric correction of a synthetic image, in which the DN is a function of the slant range distance. This image is georectified with exactly the same parameters as those used for correcting the radar image, as shown in figure 1. This image allows the rapid calculation of the slant range for each pixel of the corrected radar image. The local incidence angle  $\theta_0$  is calculated as a function of the elevation of the ground, the altitude of the aircraft and the slope of the terrain in the direction of the antenna, all inside a Geographic Information System (GIS).

Once an image of the local incidence angle is produced, a backscattering model can be chosen or semi-empirical relationships can be developed to calculate the compensation for topographic modulation of the radar return. In our first application of this methodology, we chose to consider all surfaces as lambertian, scattering the signal equally in all directions. The compensation factor to apply for intensities is then  $\cos^2(\theta_0)$ , one cosine being for the projection of the incident intensity on the sloped terrain, and the other to account for the projection, in the direction of the antenna, of the surface contributing to backscatter in the Lambertian assumption. In addition to this  $\cos^2(\theta_0)$  factor, a factor  $\sin(\theta_0)$  is applied to account for the compression of the area contributing to the backscatter. Since the DN in our images is proportional to the square root of the intensity, the factor we applied was proportional to  $[\cos^2(\theta_0)/\sin(\theta_0)]^{1/2}$ .

A georeferenced subset from line 8.3 is shown in its radiometrically uncorrected state (figure 2a), and after applying the factor described above (figure 2b). We can see that the image has been substantially flattened radiometrically, and that departure from the lambertian scattering becomes easier to track. Trees and buildings located in steep slopes now show as very bright spots, since these act as corner reflectors and not as Lambertian targets. This reduces somewhat the visual quality of the image, but allows an easier detection of such components. The corrected images show features in the very bright and dark areas that were invisible in the raw images. A refinement of the lambertian model is presently being developed to better account for behaviour in extreme values of  $\theta_0$ . More details can be found in Leclerc *et al.* (1993).

### DIFFERENTIATION OF CROPS

The capacity of identifying crops and their extent is an important element to inventories, yield and price predictions and perception of taxes by governments. Although the main users of yield forecasts are governments and agribusiness, the individual farmer can benefit from them indirectly in terms of improved price stability and improvements in the quality of advice offered by agricultural support services (Steven, 1993). Also, the sensitivity of remotely sensed images to soil conservation practices such as agroforestry and the leaving of agricultural residues on the ground after harvest could allow the monitoring of the use of these practices and could help in the identification of the areas which are more susceptible to soil erosion.

Using radar imagery, discrimination of crop types in flat and temperate regions has shown some promise, even with a single date and a single polarisation image (Brown *et al.*, 1993, Wooding *et al.*, 1988). In tropical countries, many growing stages of the same crop can be found at the same moment and in the same area, which complicates the matter further, this difficulty cumulating with microparcelation and topography. Digital per field classification has shown to have more potential than per pixel classification (Cihlar *et al.*, 1984, Ban *et al.*, 1993), and the present tendency is to use textural parameters in classification (Trietz *et al.*, 1993). In Central America, information on field boundaries is not abundant to say the least, and radar images are more likely to be of help in this respect, since the precise identification of crop can be affected by variations in growth stage.

The most obvious agricultural feature apparent on the image prints of flight lines number 8 is the clear division of fields that are separated by tree lines, fences or small roads. Agroforestry, the use of live fences, "alley" cropping, windbreakers and the presence of dispersed trees in pastures is very apparent in these images, features of which the identification is often a problem with the use of optical satellite imagery. Figure 3 shows the mottled texture corresponding to pasture and potato fields with dispersed live trees found near the summit of the Irazú Volcano.

Using tone, texture and context in visual interpretation, the following classes could be distinguished: forest, local agriculture, exportation

crops, and urban extensions. The shape and size of the fields and way in which they are divided are elements that can greatly help in identifying crop types. For example, the exportation crops coffee and sugar cane are often cultivated in large extensions. In our study area, the vegetable crops were cultivated in smaller fields, often separated by tree lines, and a large variation in tone could be seen from one field to another. In the windy region north of Cartago, the pasture fields were also separated by tree lines but had very low tone variations between parcels. In other parts of the images, the pastures covered extensive areas uninterrupted by fences or tree lines but had a much smoother texture than the forest areas.

In order to look into how tone and polarization contrasts can help identify crops, the study was focused on a limited number of control sites that had been submitted to "ground truthing" during the image acquisition period. One of the advantages of participating in a project such as Proyecto Radar/Costa Rica/Canada was to be informed of the date and time of acquisition of images, permitting the synchronization of extensive field measurements.

Measurements were conducted in a total of 13 test sites, each grouping an average of five fields, in order to help the later interpretation of images. All of the test sites were comprised in the overlap of at least two of the flight lines, six of the sites were covered by all three of them. The sites in which field work was conducted included one sugar cane, four coffee, four vegetable crops, one pasture and one large bare soil site which was prepared for urban development. The field data was collected in two levels (Beaulieu *et al.*, 1993): a) field measurements conducted in a limited number of control parcels, in the period surrounding the image acquisition (slope and aspect of terrain, plant spacing, row spacing and orientation, growth stage) and at the moment of the flight (soil moisture content, roughness of bare soil, plant height, 90 minutes before and after the flight, with the help of 15 persons). For this field work, a simple roughness meter was developed; b) oblique aerial photography and videography of the sites and their surrounding from a small plane, two days after the acquisition of the radar images.

Nine of these control sites were chosen for visual analysis of the images, and the corresponding subscenes were cut out from the digital data. The visual interpretation of these subscenes was carried out with the IDRISI raster GIS package, displaying the HH polarization in the green and blue channels and the VV in the red, with a linear contrast stretch and 1% saturation.

In the case of coffee, very little variation was observed between fields which yet had significant differences in their plant height or health state. In certain cases, striping could be observed in fields that had been submitted to a renewal practice called "Rock'n Roll", involving the total trimming of one out of every three rows, trimming of the next row at breast height and leaving the third one at its full height. In one case where an entire field had been submitted to a total trimming and was invaded by weeds, a higher response

in VV was evidenced by a reddish colour in the displayed colour composites. This reddish colour was also apparent in overgrown pastures which were adjacent to one of the plantations. The same effect was even more intense in a large marshy high grass patch occupying a depression in one of the coffee farms. This could be explained by the fact that the grass and the weeds have a greater number of vertical constituents than the coffee bushes permitting better coupling of the VV waves with the vegetation. Following Bakhtiari and Zoughi (Bakhtiari and Zoughi, 1991) who have modeled radar backscatter in high prairie grass, this effect should be visible for incidence angles greater than 40° in C-band, which is the case of our images.

In the case of vegetable crops, radar images can show a clear distinction between smooth bare soil (dark), young plants (intermediate brightness) and fully developed plants (bright), as can be seen in figure 4. In other sites where the bare soil fields which had been recently ploughed and were rough, the difference in intensity between them and the developed vegetation was smaller, but still obvious in most cases.

In the sugar cane test site and surrounding fields, the most obvious feature was the fact that the recently harvested fields still covered with residues had a much more intense green colour, indicating a pronounced superiority of the HH backscatter over the VV. Again, this can be explained by the fact that the residues are long sugar cane leaves, horizontally laid down on the ground. Also, many of the mature sugar cane fields appeared darker than the rest of the image. This, as well as the fact that all of the surrounding fields are owned and managed by one single company, Hacienda Juan Viñas S.A., led to interest in conducting a more detailed and quantitative study specific to the sugar cane crop.

## GROWTH STAGES IN SUGAR CANE

A quantitative study was conducted in the surroundings of the sugar cane site, considering a great number of additional fields, for the objective of observing the effect of the growth/intervention stages on radar backscatter intensities. This was made possible by the fact that the company Hacienda Juan Viñas S.A., which manages over 1500 Hectares of sugar cane in the Turrialba township, maintains weekly records of the activity carried on in each field. This more quantitative study was not only motivated by the availability of data but also by the importance of the sugar cane crop in Costa Rica and the Caribbean. Its inventory and monitoring are needed for management and economic predictions, and the cloud cover present in these regions makes radar an attractive tool.

Although we had taken field measurements in only six of these fields and had oblique areal photography and video of only 60, we were able to carry out a quantitative study of 130 fields by carefully analysing the agronomic records of the farm. Out of the extensive area managed by Hacienda Juan Viñas, we only considered four farms, covering a total of 680 ha, which were covered by the overlap of flight lines

8.2 and 8.3. This area also coincided with the south-eastern limit of coverage of the Costarrican territory by 1:10000 maps which were published in 1992, and produced from aerial photos acquired in 1989 (IGN and JICA, 1992). The portion of this area that is cultivated with sugar cane is neither flat or extremely abrupt, making it an excellent test site for the radiometric corrections described above. Radiometric corrections, both for topography and antenna pattern, were necessary to make any quantitative measurement of the radar signal, especially to compare the intensities from different fields.

In addition to the radiometric corrections of topographic effects, a speckle reducing 5x5 Lee filter and an antenna pattern correction were applied. To insure that the samples of radar backscatter intensity were not taken subjectively, a detailed map of the fields was digitized and integrated in the IDRISI GIS for the purpose of image parameter extraction. This map was established from the 1:10000 topographic maps Birris and Capellades and from a map Hacienda Juan Viñas S.A. had developed from 1979 aerial photography, considering indications given by the agricultural engineer of the company about changes undergone since.

In order for the images to correctly overlay the maps, a geometric correction was applied to them. Because the data we worked with were in slant range and moreover because of the pronounced topography, simple polynomial rectification techniques could not be applied. The image had to be projected in ground range, onto the irregular terrain, the latter being described by a DEM. This was conducted with the FLIGHT and STG programs in the EASI/PACE image processing package developed by PCI Inc. The DEM was elaborated with the TOSCA and INTERCON programs in the IDRISI GIS package, digitizing and interpolating within the contour lines of the 1:10000 topographic maps. Its precision has been evaluated to be of 1m in altitude.

For comparison purposes, a portion of a Landsat TM image of the 3rd of April, acquired three weeks before the acquisition of the radar images, was studied. The subscene corresponding to the study area was cut out from the digital data and geometrically rectified with a linear affine transformation.

The database which was elaborated to contain the information on the various fields included field name, date of last cut, date of last intervention (burning, ploughing, planting of new cane), age of sugar cane, state of the field, observations from oblique photographs, and age at the moment of acquisition of the Landsat TM image. The fields that presented portions of different ages were divided into homogenous polygons when their limits were identifiable features on the topographic map (roads, streams, etc). Once the plan was elaborated, a 8m buffer zone was removed from the perimeter of each polygon, to avoid edge effects and the inclusion of roads or fences into the samples. A total of 140 polygons were defined and used for extraction of image intensity means, of which 130 were cultivated with

sugar cane, the other being soccer fields, forest and pasture patches.

The average DN for each polygon was extracted from the four radar images (8.2 and 8.3, each in HH and VV). An image of a ratio we call Normalized Difference Polarization Index ( $NDPI = (HH - VV)/(HH + VV)$ , Beaulieu *et al.*, 1993) was calculated for each flight line, and an image of the Normalized Difference Vegetation Index ( $NDVI = (TM4 - TM3)/(TM4 + TM3)$ ) was calculated from the TM image. The average values for each polygon were also extracted from these images.

For the five images, the value of these parameters was plotted in function of the age of the sugar cane. The fields undergoing renovation (rough bare soil) were given an age value of -5 whereas the recently harvested fields which were still covered with residues were given a value of -2, to better separate them from the fields which had been submitted to burning of residues (age = 0). At the moment of the radar flight, none of the fields in the database were covered with burnt residues.

The graph of average DN for each parcel in function of age showed a large dispersion of values (figure 5a,5b). When the fields were grouped by age ranges, as shown in figure 5c and 5d, a slight tendency to an increase in backscattering intensity in the first months of growth and then to a decrease with maturing of the cane could be observed, except in the case of line 8.2 (where the site was in far range) in HH. No statistical tests have been run on the data to check if this tendency was significant. The only parameter which shows promise to significantly distinguish one class from the others is the NDPI, which was almost invariably higher in the fields covered with residues. The great dispersion encountered in the radar backscatter intensities could be due to an imperfect radiometric correction, to topographic features finer than what the DEM can account for, and for differences in water content in the soil and vegetation. Indeed, the images had been acquired after a rainy weekend, a condition which emphasizes differences in drainage and water retention capacities. We expected to find a much greater distinction between the bare soil and mature cane, to say the least. Nevertheless, the tendencies observed in the graphs are consistent with the observations made with visual interpretation of the images, and we expect to obtain better results in dryer (more uniform) conditions and flat terrain.

The graph of the NDVI calculated with Landsat TM in function of sugar cane age showed a much more significant dependence between both parameters, as can be seen in figure 5e and 5f. The dispersion of values for a same age has been attributed to the absence of radiometric correction for topographic effects, variations in fertilization and variations in leaf yellowing age between varieties. We are now in the process of refining this analysis.

#### DISTINCTION BETWEEN BARE SOIL AND DEVELOPED VEGETATION

From the previously discussed results arises the following question: in the radar images, why did the

bare soil appear different from the vegetation in the vegetable crop sites and not in the sugar cane site?

We are presently analyzing the data described in the previous section to study the effects of soil moisture, soil roughness and incidence angle. Although the quantitative results are not yet ready to publish, the qualitative observations suggest that separability increases with incidence angle, and decreases with soil roughness and water content. The main difference between the bare soils in sugar cane and in root crop was their water content. At the moment of the flight, the average water content of bare soils was  $0.45 \text{ g/cm}^3$  in the sugar cane fields and  $0.12 \text{ g/cm}^3$  in the vegetable crop fields. It had very recently rained in both locations, but the difference in water content can be attributed to the fact that the weather was sunnier and more windy in the vegetable crop region during the acquisition of the images (the soil was dry only in the upper 5cm), and that the sugar cane soils were very rich in organic matter, providing them with a better water retention capacity.

The fact that each site was covered by two or three flight lines allows the study of the influence of incidence angle on the radar return. In the subscenes covering the root crops, the smooth soils were very dark in both of the flight lines in which they were encountered as much in near range (low incidence angle) (figure 4) as in far range (high incidence angle). The recently ploughed fields were less dark, but still distinguishable from the vegetation, in far range. In near range, this contrast was less obvious because of an increase of backscatter exhibited by the rough soil. This could be explained by considering the Rayleigh and Fraunhofer roughness criteria that state that electromagnetic roughness decreases with wavelength and local incidence angle, so a given area offers a rougher surface in near range than in far range (Bonn and Rochon, 1992). The renovated sugar cane fields were very moist and very rough, and appeared bright in far range as well as intermediate range. We are planning to extend our study to sugar cane fields in a dryer and flatter region in Costa Rica to investigate if the bare soil fields can be better distinguished in these conditions.

## MAPPING OF SWEET BANANA AND PLANTAIN BANANA PLANTATIONS

With more than 71 million tons produced per year, sweet banana (*musa AAA*, later referred to as banana) is the most important fruit production volume in the world (Loeillet, 1992). There are more than 100 producing countries in the 5 continents, all located in tropical and intertropical regions. Exported towards the developed countries as well as consumed by the locals, the banana plays an important role in the nutritional balance and in the economy of the producing countries. In Costa Rica, banana exportation is the highest source of foreign income. Plantain banana (*musa AAB*, later referred to as plantain), which is almost exclusively consumed locally, is an important part of the Costarrican diet. The importance of the monitoring of these crops at the national level is then unquestionable.

Although the extent of the areas cultivated

with banana are relatively well known, they are not regularly brought up to date. With the continuous expansion of the cultivated areas by the banana companies, the produced maps and calculated areas quickly become out of date. In spite of the importance of banana in the country's economy, Costa Rica did not yet institute a mechanism to map and follow the expansion of production zones at the national level. In the case of plantain banana, the case is much worse. There is very little knowledge of the surfaces planted with this crop, generally cultivated in an artisanal manner.

Whoever has seen a radar image of a banana producing region for the first time surely was surprised by the very intense brightness of the crop, probably resulting from the large leaf area of the plant (figure 6). One can imagine that with this capability of distinguishing banana plantations from surrounding vegetation independently of atmospheric conditions, radar imagery could become a very useful tool for mapping plantations. It remained to be verified what is the precision with which plantation boundaries can be established, if it is possible to distinguish different stages of production and to distinguish banana from plantain.

The images that were used for the present study are flight lines 2.1 and 2.2, acquired in nadir mode, and the study areas were located near the Atlantic coast of the country. Before any digital treatment, the subscenes corresponding to the nine studied banana plantations and four plantain plantations were displayed on the screen (HH in red and VV in green and blue). The banana plantations could be easily identified because of their brightness and geometrical shape. The roads and drainage channels within the plantations also appeared very clearly. Pre-production zones, containing plants which have not yet attained maturity (height of 0.5 m to 1.5 m) nor optimal density could also be identified because of their lower brightness (figure 7). In the case of one of the plantations, there was a darker area corresponding to soils inadequate for the crop, in which it is very difficult to maintain a high plant density. We could therefore infer that radar is sensitive to plant density. On the other hand plantain, which is planted with a higher average density than banana, (typically 1800 to 1900 plants/ha whereas banana plant density is usually between 1700 to 1800 plants/ha.), appeared darker. In certain cases, we found a confusion between plantain and homogenous forest. In addition to being planted in an almost random manner, the plantain plantations usually had irregular limits, which made their delineation difficult, especially when they were surrounded by open homogenous forest.

For our small subsets which were for the most part in medium range and in flat terrain, we tried a linear affine rectification to 1:50000 topographic maps with the IDRISI GIS. With four control points, we reached in average an RMS error of 4 meters, which we considered acceptable for this study. The digital delimitation of field limits on the screen permitted to quickly obtain a precise and georeferenced map of the production zones of individual plantations with a low

cost software. Larger areas would need at least a geometric correction to project the image from slant range to ground range.

To study the possibilities of a more automatic mapping, various supervised and unsupervised classifications were run on the subsets, using both polarizations. The classifications obtained from the unfiltered data had a salt and pepper aspect, with a great number of dots corresponding to different classes inside the plantations as well as outside. The classification was greatly improved by prior application of 7x7 median or Lee filters to the images. In this way, a better uniformity was reached inside the banana plantations but two different classes still remained within them. The class corresponding to a slightly lower brightness also was attributed to the plantain plantations, to banana in pre-production and to areas with low plant density. When removing groups of contiguous pixels covering less than 2500 m<sup>2</sup>, the results obtained were excellent, which indicate that an automatic classification of production zones in banana is feasible. When contracting the images by a factor 8, creating new 32 m x 34.48 m pixels containing the average DN of 64 pixels of the initial image, the classifications provided unambiguous data, suggesting good results should be expected with filtered low-resolution satellite imagery (figure 8). From these latter classifications, the area of banana in production was evaluated for the nine plantations.

The calculated areas were compared with the areas calculated from digitized and georeferenced plans of the respective farms, with the areas appearing in the legends of these plans, and with areas provided by the managers of the farms. The discordance often found between the values obtained from these three sources showed the need to develop a uniform method for the estimation of production areas, a need which is not unique to Costa Rica (Valdivieso, 1993). We think adequately georeferenced satellite radar imagery can provide the precision needed for this purpose.

## DIAGNOSIS OF BLACK SIGATOKA INFECTIONS

The main disease affecting banana and plantain crops is the Black Sigatoka (*Micosphaerella fijiensis*), a fungus which produces important leaf necrosis, slows down the growth of the fruit and significantly reduces yield. A National Commission was created by order of the Costarrican Government to look at the solutions for the prevention and the fight against black Sigatoka, has recognized the necessity of the government's involvement through a Declaration of National Emergency in response to the crisis the sector is facing as a result of this disease (CORBANA, 1993).

For the moment, the infestations of Black Sigatoka are not monitored at the national level because of lack of resources and the unknown location of many production zones in the country. Radar, because of its sensitivity to water content and to the geometry of targets (in this case the leaves of the plants), could be a significant tool for this monitoring.

For this study we extracted the average of HH and VV digital numbers in three to eight samples of 100

pixels in each field. During field inspections, the severity of infestations is expressed by a parameter called PPI (Promedio Ponderado de Infección), which is a measure of the proportion of leaf area affected by the fungus. This parameter was provided to us by the farm managers for each field for April 1992. When the average brightness values were plotted against PPI, a tendency to decreasing brightness with increasing PPI, particularly in the VV polarization, was observed (figure 9). We need to pursue this investigation with radiometrically corrected data in order to confirm these observations. More details on our banana and plantain study can be found in Pigeonnat (1993).

## GENERAL CONCLUSIONS

Our studies have shown that one of the most promising agricultural application of radar imagery in tropical regions is the mapping of banana plantations, because of the very high brightness exhibited by this crop. The use of polarization contrasts has a potential role for the identification of recently harvested sugar cane fields covered with residues and for distinguishing overgrown pasture from coffee. High resolution radar imagery has a definite potential for monitoring soil conservation practices such as agroforestry and the leaving of residues on the ground after harvest. The possibility to distinguish bare soil fields from developed vegetation with radar images seems to increase with decreasing soil roughness and water content as well as with increasing radar incidence angle. The radiometric corrections developed to compensate the effects of topography significantly improve the possibility of monitoring crops in mountainous regions, and could be of benefit to many areas other than agriculture.

Our continuing efforts are directed towards the refinement of the radiometric corrections, the better understanding of the sensitivity of polarisation contrasts to crop geometry in function of radar incidence angle, the better understanding of how local incidence angle, soil moisture and roughness affect the possibility of identifying bare soil areas, and the development of a specific project on the use of satellite imagery for the mapping of banana plantations and monitoring of Black Sigatoka infection.

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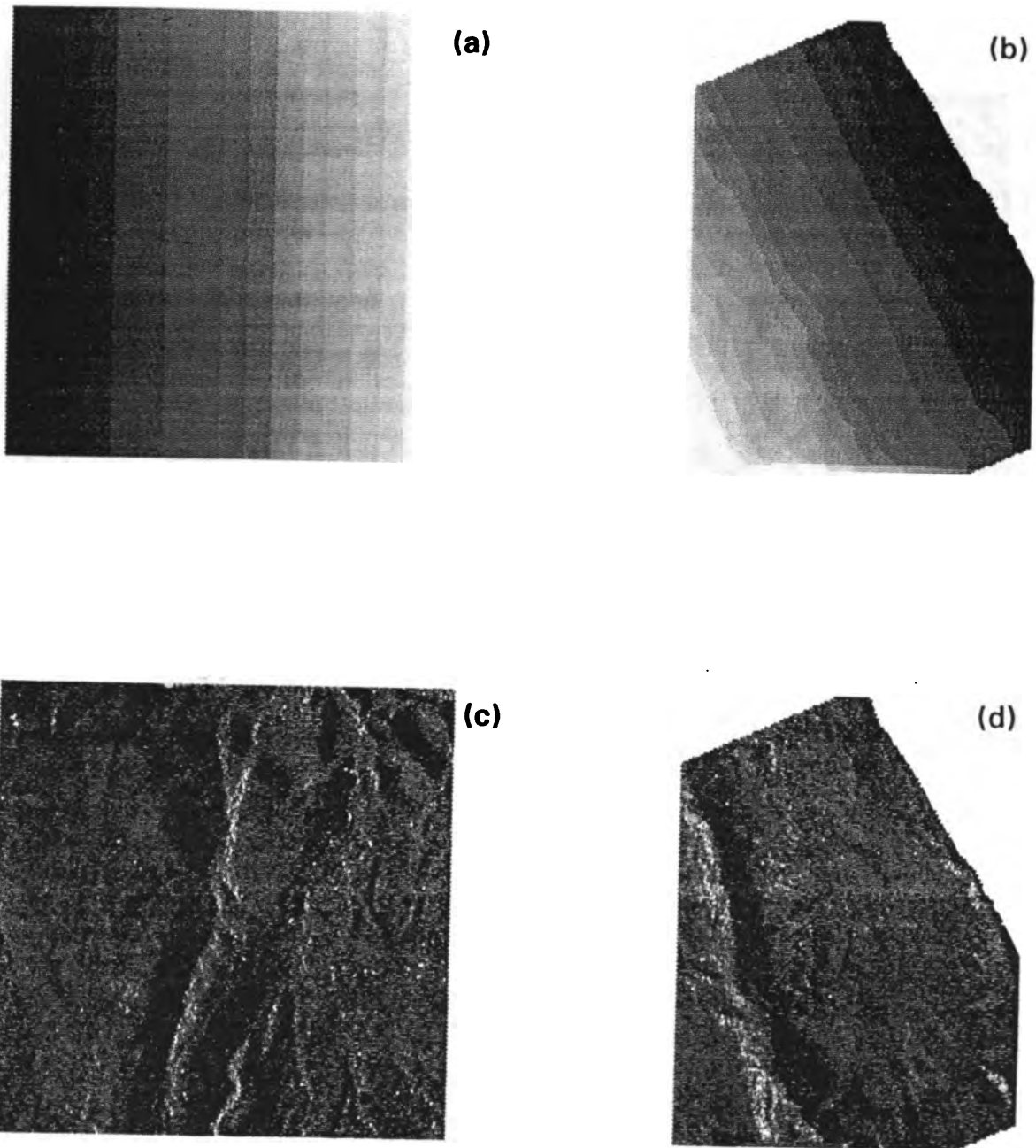
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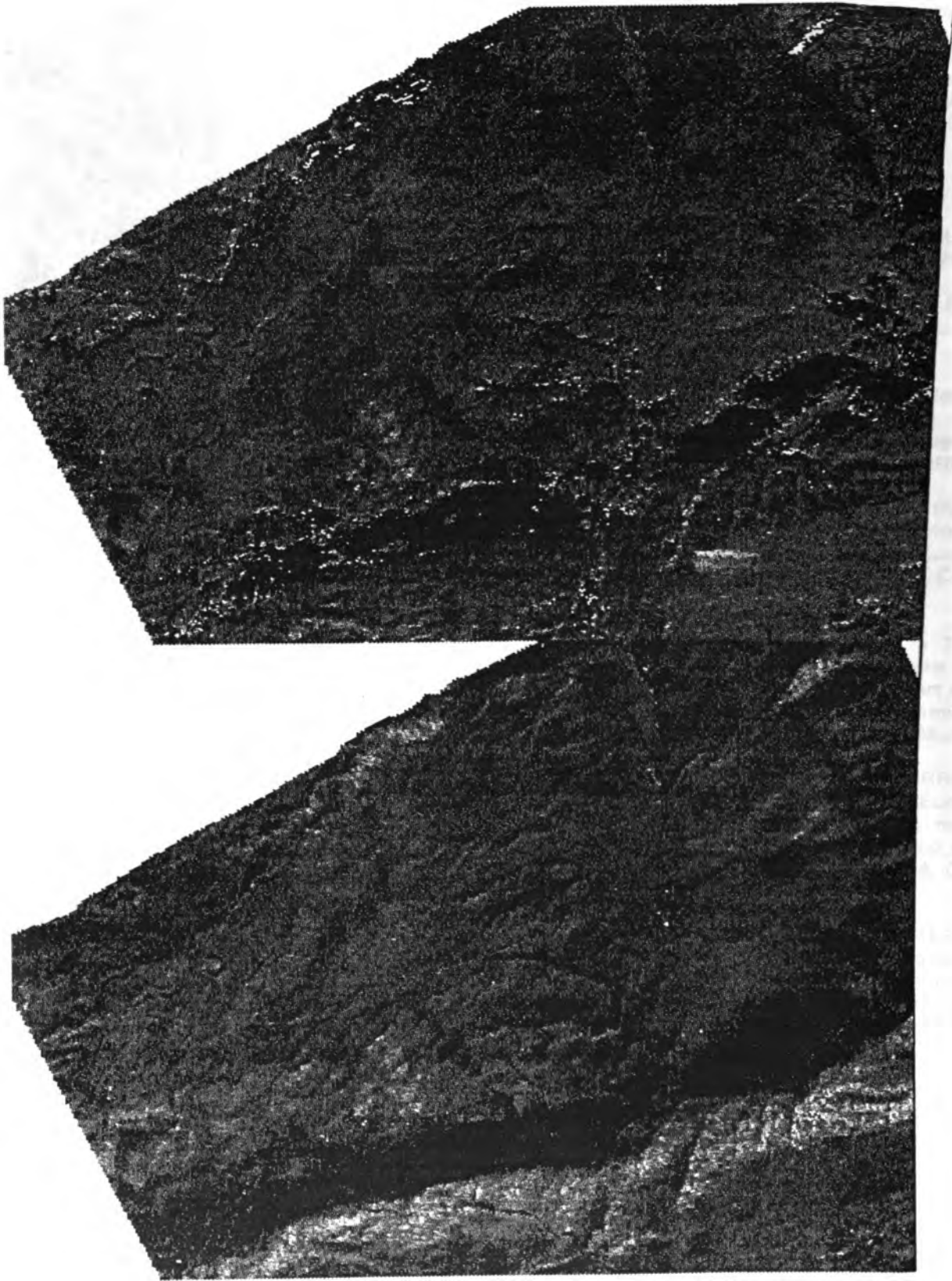
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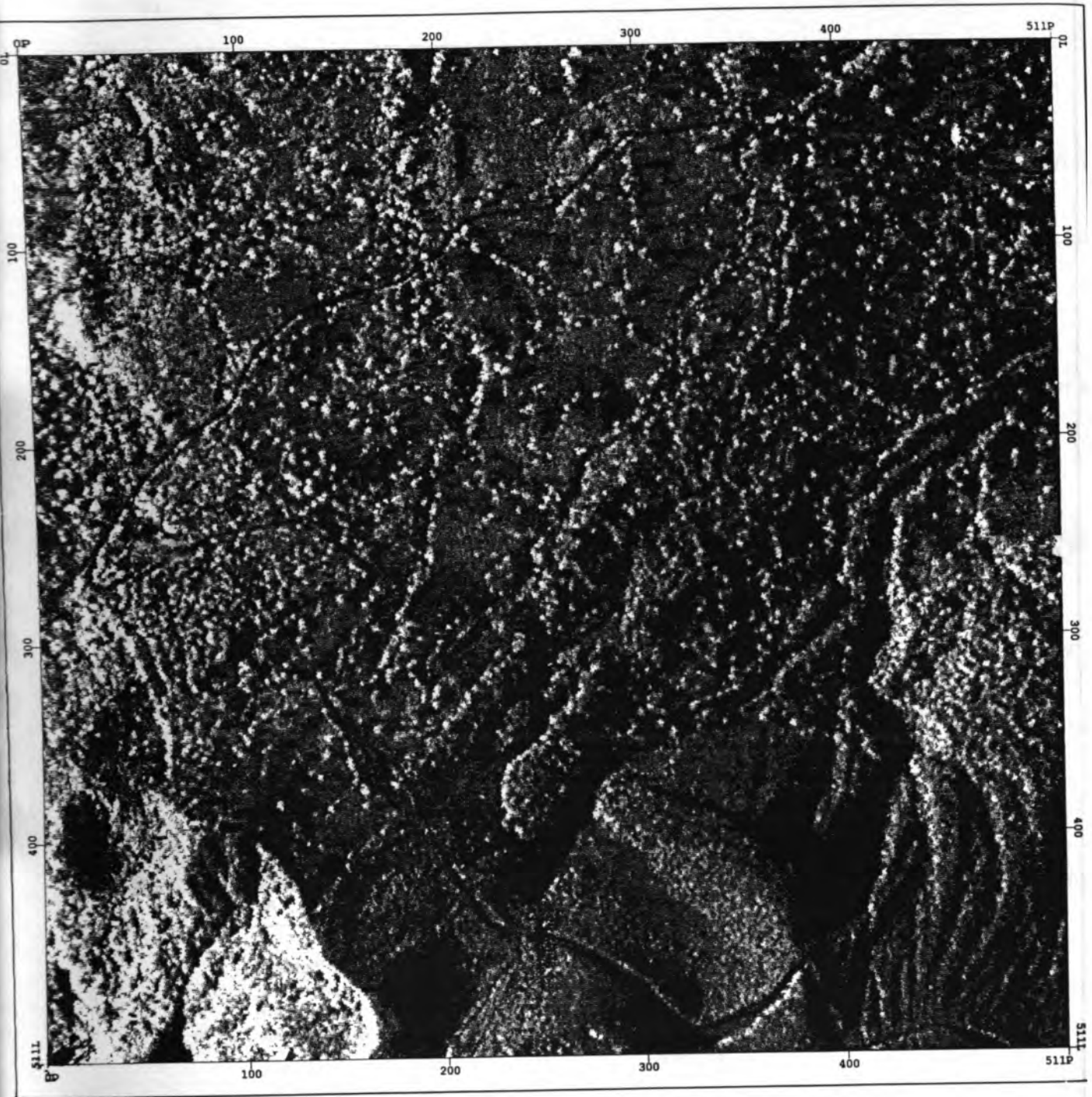




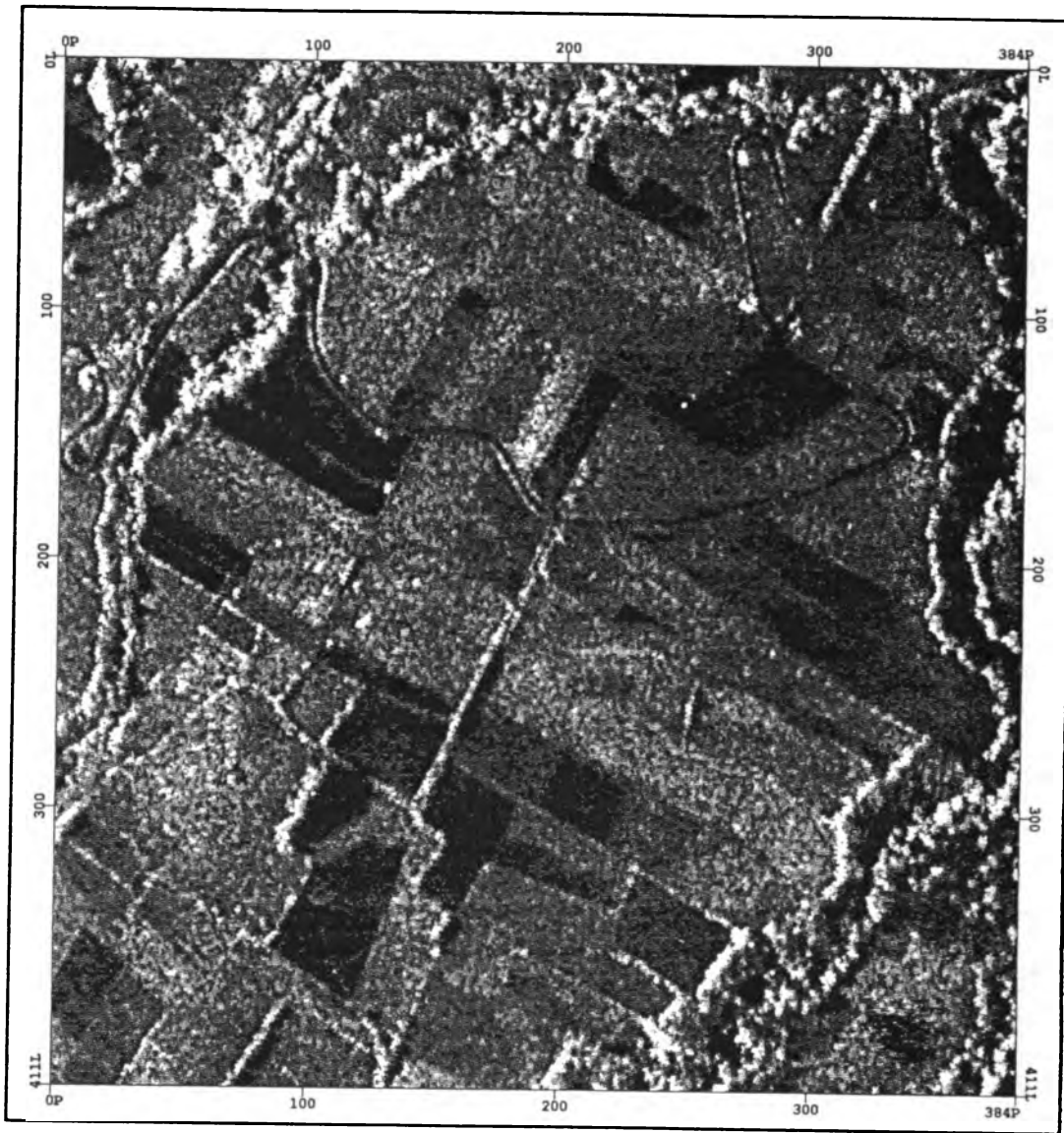
**Figure 1:** Use of a synthetic image to allow rapid calculation of the slant range in geometrically corrected images: the synthetic slant range image (a) in which the slant range distance is proportional to the DN, is geometrically corrected (b) with the same parameters as those used for geometrically correcting the radar image (from c to d).



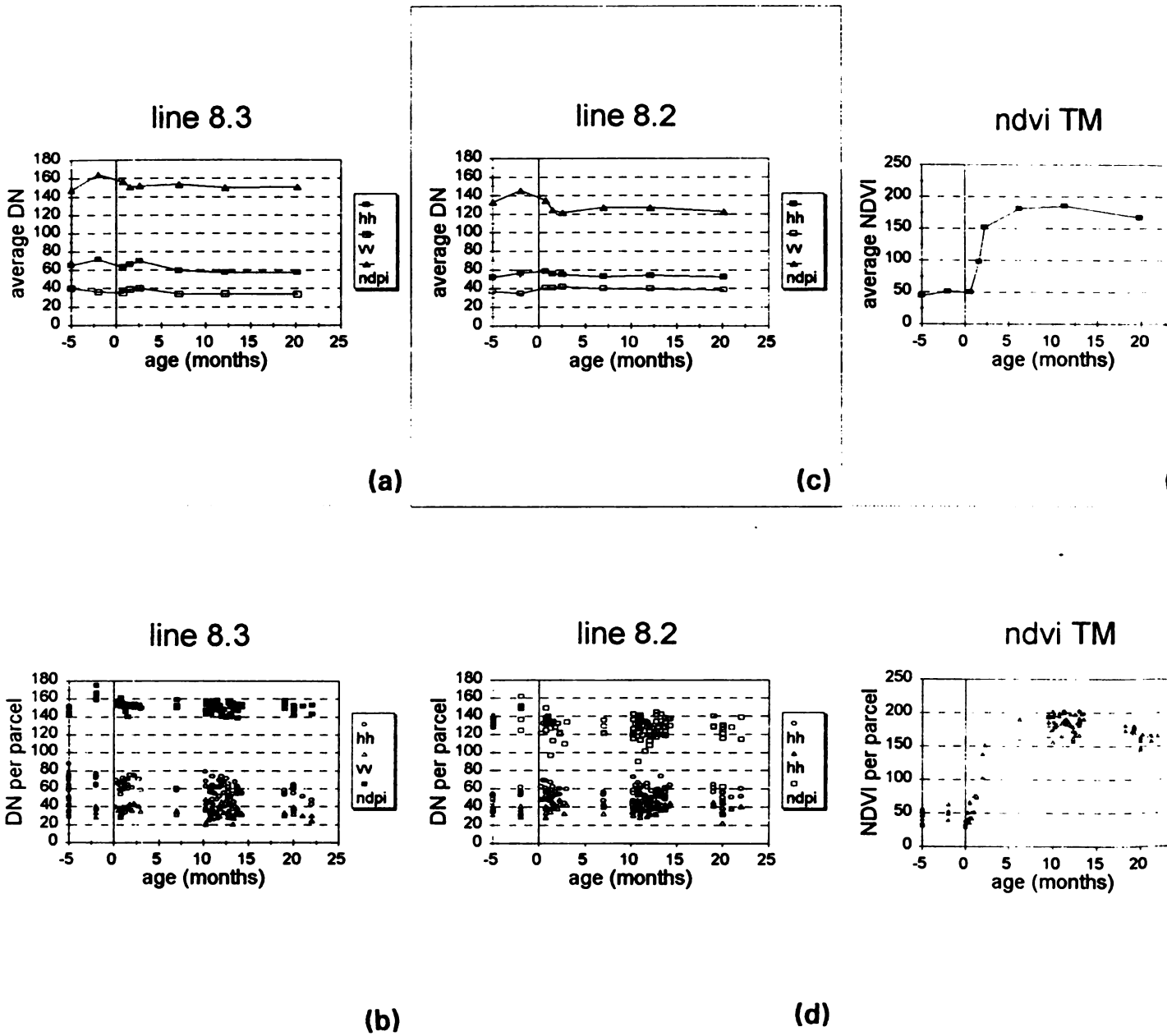
**Figure 2: Georeferenced HH polarization radar image subset of the Juan Vinas area in: (a) radiometrically uncorrected, and (b) corrected states.**



**Figure 3:** Raw HH polarization radar image subset of potato and pasture fields with dispersed trees, a few kilometers from the crater of the Irazú Volcano, showing a characteristic mottled texture.

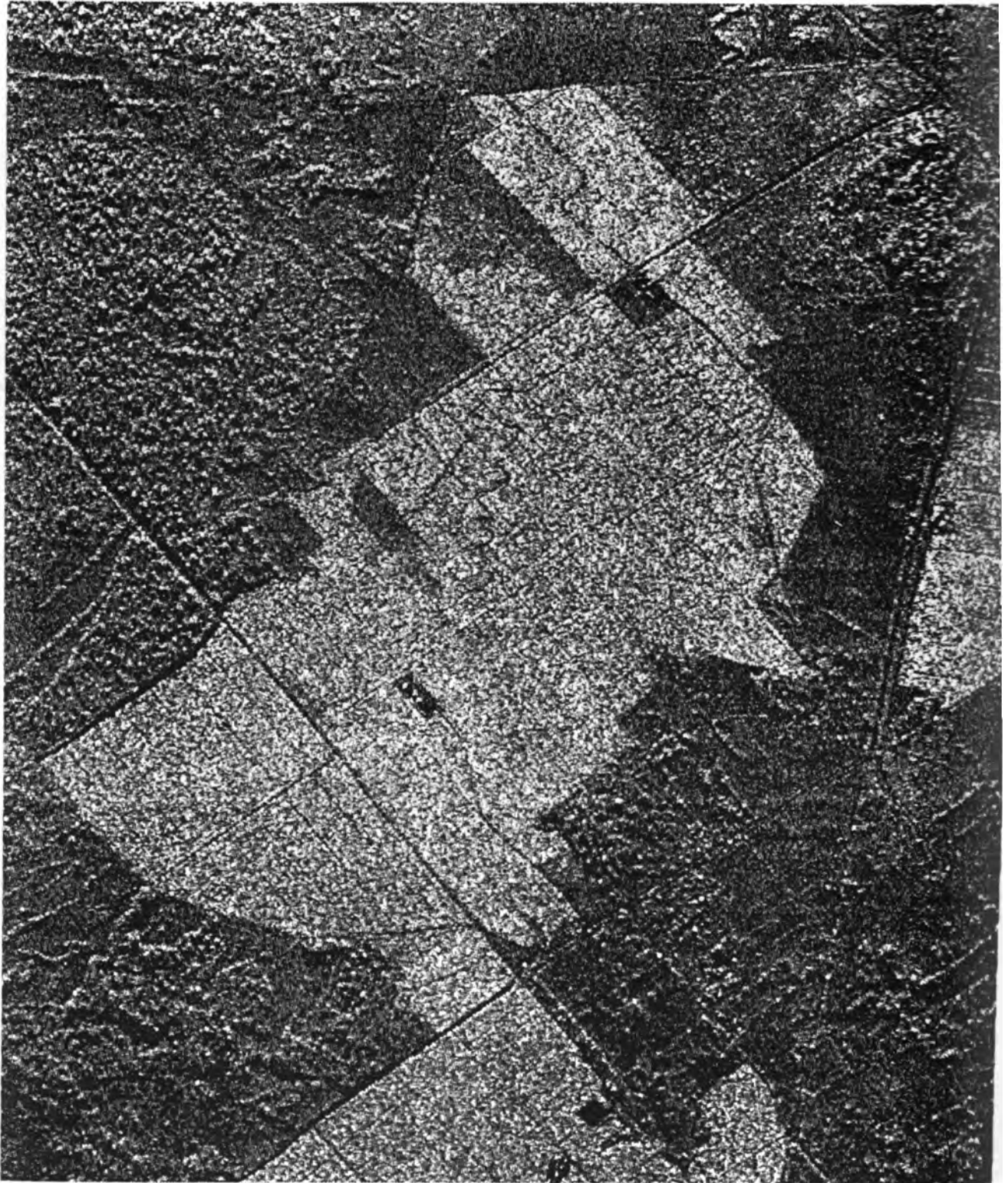


**Figure 4:** Raw HH polarization subset of potato fields in near range, narrow mode. Smooth dry soils appear dark, fields with young plants have an intermediate brightness and fields with well developed plants appear brighter.



**Figure 5:** Graphs of image parameters in function of age and intervention stages in sugar cane. age=-5 for renovated fields (moist rough bare soils), -2 for recently harvested fields covered with residues. Here the NDPI values are computed as follows:  

$$NDPI = ((HH - VV) / (HH + VV)) * 200 + 100$$



**Figure 6:** Raw radar image subset of La Guaria banana plantation. Areas in production appear very bright. Banana plantations usually have a geometrical shape.

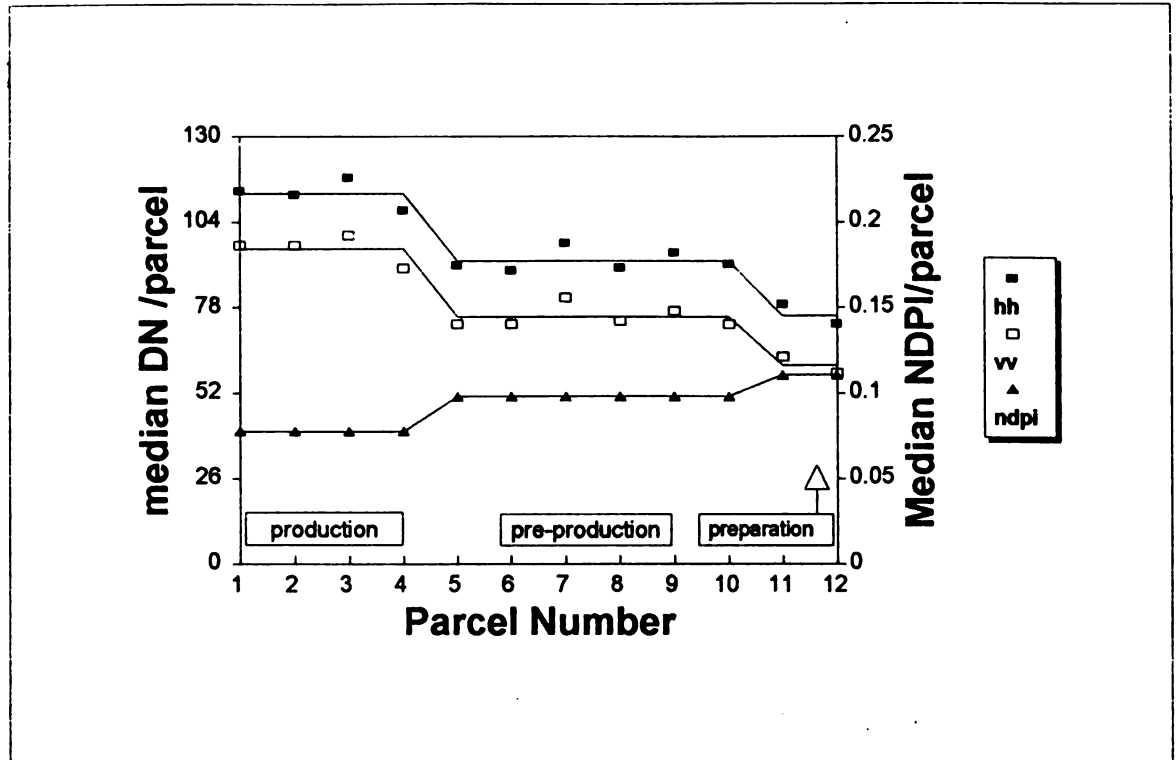


Figure 7: Graph of median Digital Number in individual parcels, in function of production stage for the Turqueza Dorada banana plantation.

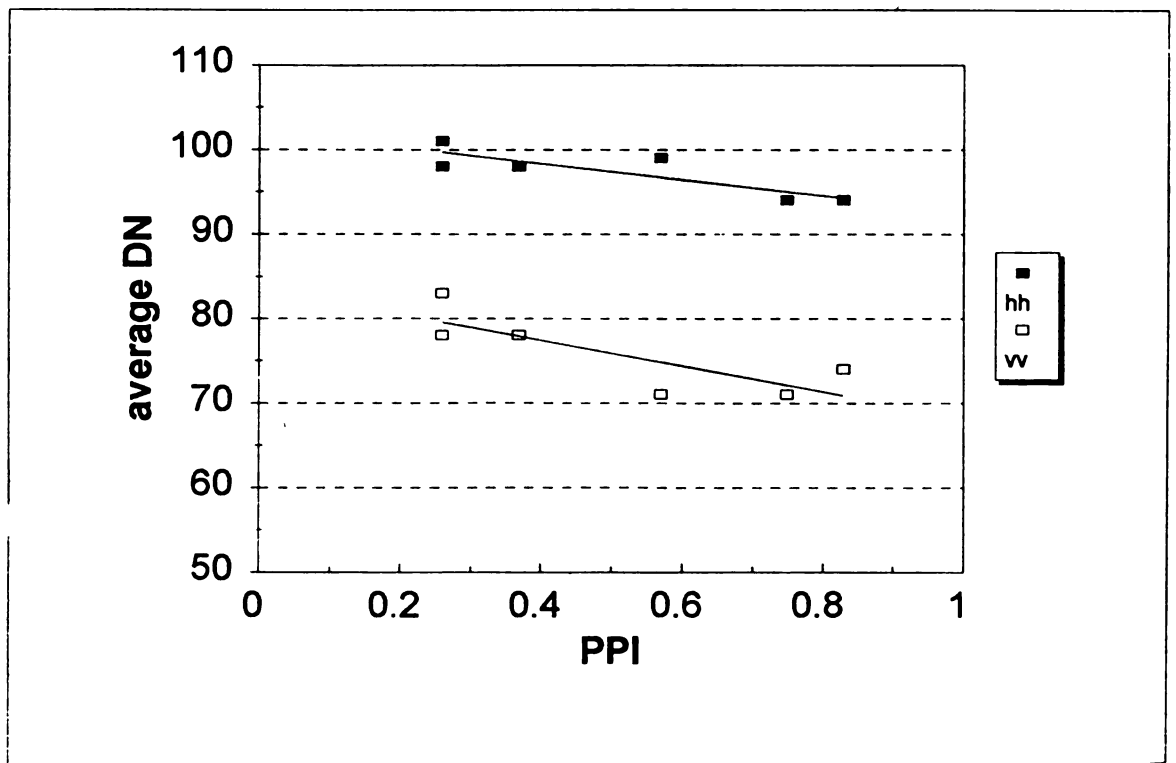


Figure 9: Graph of average DN (for 3-5 sampling sites per plantation) in function of the PPI (indicator of the level of infection by Black Sigatoka) in several banana plantations.

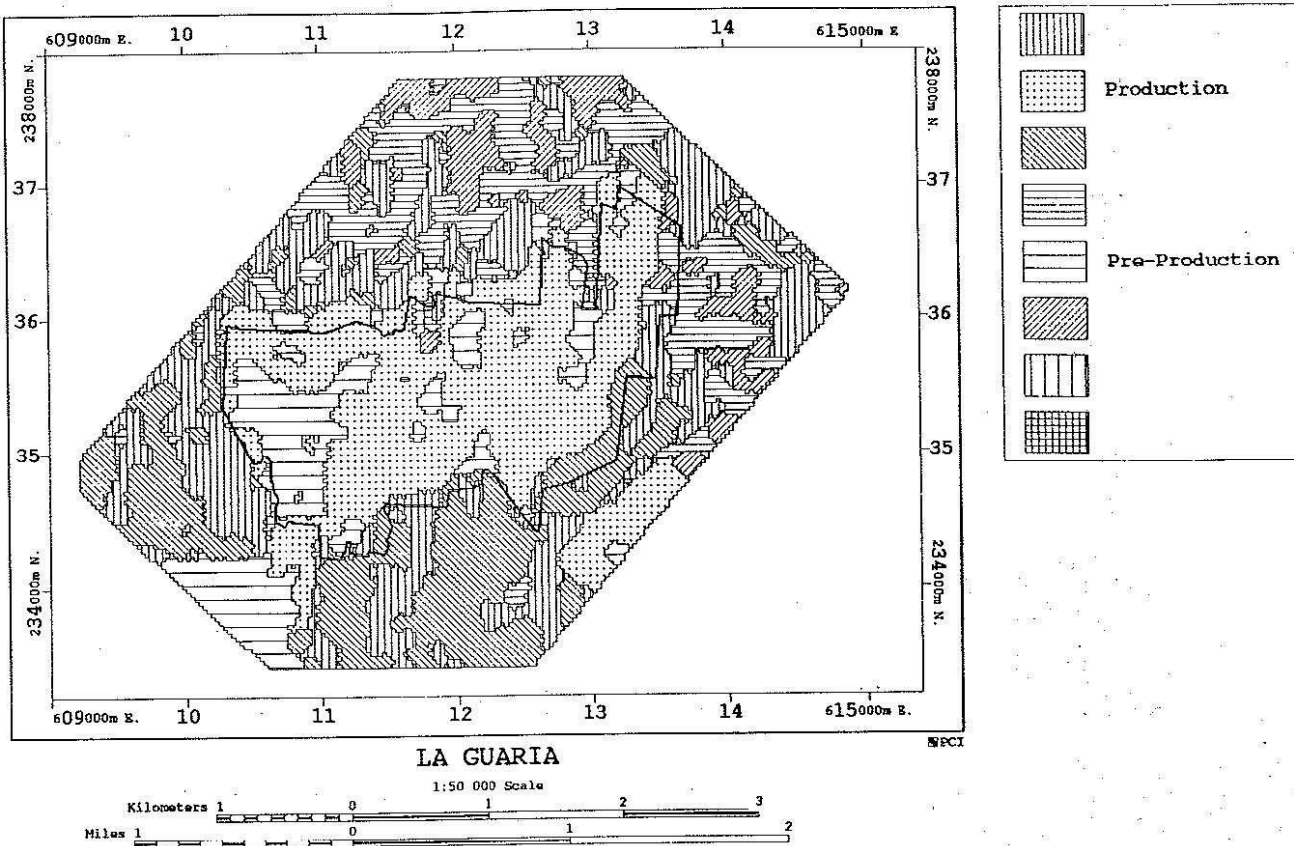


Figure 8: Georeferenced unsupervised classification (using CLUSTER of the IDRISI GIS) of the subset corresponding to the La Guaria plantation, with image contracted by a factor 8. The vector superimposed to the classification is the contour of the plantation, taken from the digitized map of the farm. Radar image and farm map have been georeferenced independently, and offset is attributed to positioning errors in the farm map.