Nighttime lights - DMSP Satellite Data as an Indicator of Human Activity in the Brazilian Amazonia: relations with population and electrical power consumption.

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Abstract

This paper describes an assessment of the DMSP/OLS nighttime satellite imagery as evidence of human presence and activity over the Brazilian Amazonia region. The study explores the potential of the sensor on a regional scale, and verifies the correlation between DMSP nighttime light foci and population and between nighttime light foci and electrical power consumption. Using a mosaic of DMSP/OLS nighttime light imagery from September 1999, 248 towns from a total of 749 *municípios* in Amazonia were detected. It was found that the nighttime light foci were related to human activity, including urban settlements, mining, industries, and civil construction. Restricting the analysis to the state of Pará and excluding outliers, a linear relation (R^2= 0.79) was obtained between urban population from the 1996 Census data and DMSP nighttime light foci. Similarly, electrical power consumption for 1999 was linearly correlated with DMSP nightlights foci (R^2 = 0.79). It may, thus, be concluded that DMSP/OLS imagery can be used as an indicator of human presence in the Amazonia region in the analysis of spatial-temporal patterns in Amazonia because they are closely related to urban population and electrical power consumption. Remote sensing imagery is useful, considering the continental dimension of Amazonia, the absence of demographic

information between the official population census (taken at a 10 year interval), and the dynamics and complexity of human activity in the region. DMSP nighttime light foci can be a valuable data source for studies, modelling, and planning activities where the human dimension must be consider throughout Amazonia.

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Keywords: DMSP/OLS nighttime light, human settlements, urban population, electrical power consumption, urban Amazonia, spatial analysis, regional scale.

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1. Introduction

The Brazilian Amazonia supports the world's largest contiguous area of untouched tropical forest. However, recent estimates indicate deforestation rates of 1 to $3x10^6$ ha $year^{-1}$ for the period of 1991-1999 and the loss of approximately $6x10^7$ ha (more than half a million km^2) of forest by 2000 (INPE, 2002). The deforested area of the Brazilian Amazonia has increased from 10 million hectares in the 1970s to nearly 59 million hectares in 2000, following the building of an extensive road network and government-assisted migration and agrarian projects. Alves (1999) showed that 90% of the total deforestation in Amazonia has been concentrated within a 100-km land zone around major roads, increasing the environmental and social impact in such areas. The intensity of the land cover changes in the region brings serious environmental concerns, such as the carbon budget rates, the conservation of biodiversity (Capobianco et al., 2001), and modifications to the hydrological cycle, all of which have a serious impact on global climate change (Gash, et al., 1996). The human dimension of this global scenario has been considered one of the most serious environmental problems. The rapid growth in urban population has not been accompanied by an improvement in the quality of life of local populations, as demonstrated by the low indexes of health, education, and income (Browder and Godfrey, 1997, Monte-Mór, 1998).

During the last three decades, the region has experienced the biggest urban growth rates in Brazil[1]. In 1970, urban population comprised 35.5% of the total population. This proportion

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[1] For this paper, we adopted the IBGE (Brazil's Census Bureau) surveys definition for urban population: every people which domicile is located outside of urban perimeter (defined by law) is counted as urban population (IBGE, 1995).

increased to 44.6% in 1980, to 58% in 1991, to 61% in the 1996, and to 68% in 2000[2]. The increasing diversity in economic activities and the subsequent population density have reorganized the network of human settlements all over the region. Current 21st century data shows patterns and spatial arrangements that reveal a different Amazonia from those of the last decades. This new Amazonia emerges as a tropical forest with a complex urban system in the making, a perspective that has led some researchers to put forward the claim for an “urbanized forest" (Becker, 1995).

Measures of urban growth and population in Amazonia however have been dependent on census data, collected typically on a 10-year interval. Additionally, census tracts in the region frequently cover a mixture of urbanized areas and large uninhabited ones, making it difficult to produce realistic representations of the spatial distribution of the population. Given the rapid growth of urban settlement in Amazonia and the strongly asymmetrical spatial patterns of the human settlements in the region, it is therefore natural to inquire whether there area any innovative data collection techniques that could provide timely indications of urban growth as well as depict changing spatial patterns.

The spatial and temporal dimensions of the occupation processes in Amazonia suggest the use of remote sensing data provided by the Defense Meteorological Satellite Program (DMSP), with the Operational Linescan System (OLS). The OLS sensor is particularly interesting because it is sensible to faint nighttime light. It generates images with wide swath, and its images can present spatial resolution of up to 1.0 km. The nighttime satellite data provided by the DMSP/OLS has been successfully used for global/continental urban mapping,

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[2] Population data for this paper was obtained from IBGE (Brazil’s Census Bureau) surveys.

showing linear relations with other socio-economic variables such as population, Gross Domestic Product, and electrical power consumption (Imhoff et al., 1997, Sutton et al., 1997 and Elvidge et al., 1997a).

This Amazonia study evaluates DMSP/OLS imagery for detection of human activity in Brazilian Amazonia. Two questions were posed. First, on a regional scale, what relationships between DMSP/OLS data and population and energy consumption are attained? Second, what are the local conditions and data calibration needed to use DMSP as a valuable data source for further projects, such as planning regional development and modelling land use conversion?

In this paper, we show that all DMSP nighttime light foci are related to human activities, including urban settlements, mining, and civil construction. Additionally, if the outliers for the region are identified and excluded from the data set, linear regressions can be established between DMSP nighttime light with urban population as well as between DMSP nighttime light and electrical power consumption. Our analysis suggests that DMSP nighttime light can be used as a reference of human activity throughout Amazonia, within specified constraints.

2. DMSP/OLS for urban mapping and human activity detection

The U.S. Air Force Defense Meteorological Satellite Program (DMSP), which includes the Operational Linescan System (OLS) - an oscillating scan radiometer capable of detecting the visible and thermal-infrared emissions, has been in operation since the 1970s. The spatial resolution of 2.8 km at full mode, and 0.56 km at fine mode, associated with approximately 3000 km of swath, enables the synoptic coverage of large areas. The visible spectral band (VIS: 0.4-1.1 μm) signal, intensified at night using a photomultiplier tube, makes the sensor very sensitive to faint VNIR emission sources (Elvidge et al., 1997b) such as those produced by the nighttime light of cities, towns, fires, lightning, etc. The high contrast between lighted and unlighted areas and the sensor's spatial resolution makes it a useful tool to identify regions of significant human activity (Croft, (1973) and 1978).

Early attempts to use a single data acquisition of DMSP/OLS imagery to map the distribution of human settlements and the spatial distribution of human activities, such as energy consumption were hampered due to problems of pixel saturation and blooming, cloud cover, and the presence of ephemeral light sources such as lightning and fires (Welch, 1980, Foster, 1983 and Welch and Zupko, 1980). The problem with ephemeral lights and cloud cover has been solved by the NOAA/NGDC (National Oceanic and Atmospheric Administration's National Geoscience Data Center), which developed a methodology to generate stable light data sets. This method includes the collection, rectification, and aggregation of a large number of nighttime OLS images. The image time series analysis distinguishes stable lights produced by cities, towns, and industrial facilities from ephemeral lights. This methodology also accounts for cloud screening and ensures sufficient cloud-free observations for determining the location of all VNIR emissions (Elvidge et al., 1997b). The result is an image whose values are percentages of nighttime light occurrences for each pixel. These images where used by Imhoff et al. (1997) to map urban areas in the United States, by interactively identifying the lowest threshold value in the urban/not urban classification that maintains the urban core as a unit. Compared to the urban areas from the 1990 U.S. Census, the urban area from DMSP nighttime light was only 5% smaller.

Sutton et al. (1997) obtained a quantitative relationship between the intensity of DMSP nighttime light and the population density for cities of the continental United States. The correlation between nighttime DMSP imagery and human population density was attained when adjacent saturated pixels were grouped in "urban clusters" and then the area of these clusters was plotted against the population, obtaining a coefficient of determination (R^2) of 0.84 for linear regression and 0.93 for exponential regression.

Elvidge et al. (1997a) concluded that DMSP nighttime light is a feasible alternative to LANDSAT-class (30m resolution) images to identify urban settlements on a global scale. Lighted areas were compared to population, gross domestic product, and energy consumption for 21 countries with different economies. Lighted areas presented a linear relation with population (R^2= 0.85), where the outliers were countries with poor economies. Similarly, lighted areas were linearly correlated with electrical power consumption (R^2= 0.96), and gross domestic product (R^2= 0.97). These results suggested that DMSP/OLS imagery could be used to infer the global population spatial distribution, with a proper regional or national calibration. Similarly, Doll et al., (2000) observed that nighttime light data was related to CO_2 emission parameters on a global scale, as a proxy of development and urbanization, with a statistically significant correlation with Gross Domestic Production (GDP) and total carbon dioxide emission.

DMSP/OLS data has also been used to produce a worldwide population database for estimating populations at risk in the LandScan Project (Dobson et al., 2000). The distribution of the population in the LandScan project represents an ambient population that integrates diurnal movements and collective travel habits into a single measure. DMSP nighttime light, associated with road proximity, slope, and land cover defined the probability coefficients that distributed census available counts for the entire world in a population density surface.

Cellular automata and fuzzy inference techniques simulated DMSP/OLS nighttime lights as a spatially explicit indicator of socio-economic activities for China (Plutzar et al., 2000). The authors showed that satellite-based measurements of nighttime light could be used as proxy indicator to simulate future patterns of economic activities and to derive scenarios of future developments of human settlements and energy demand.

3. Methodology

The methodological procedures used in previous studies associating nightlights with urban settlements for the US had to be adapted to take in consideration the unique patterns of urban settlement of the Brazilian Amazonia region. The main methodological concerns were related to DMSP/OLS image processing, described in section 3.2. A new threshold value was sought that would create a binary image in which pixels were lighted or not. A vector approach was used where nighttime light foci were converted to a vector representation in order to enable a spatial query of the foci, with village and downtown city centres.

The first part of the methodological procedure structured a spatial database for the Amazonia region. A geographical information system - SPRING, version 3.5 (Câmara et al., 1996) supported this spatial database and made it possible to carry out all the analytical procedures, including the digital image processing and data integration described in the following sections.

3.1. Database Description

The database was comprised of three different data sources: DMSP/OLS, JERS, and LANDSAT remote sensing imagery; census data; and electrical power consumption data. JERS and LANDSAT images were used to verify the correspondence between the night light foci and the land cover class throughout the region. The main source of information was the colour compositions of bands 3(B), 4(G) and 5(R) TM/LANDSAT from 1998 and 1999, available as a 120 m spatial resolution mosaic. A JERS radar image was useful to verify regions of frequent cloud cover where there was no data available from TM/LANDSAT mosaics.

Rural, urban, and total population counts were selected from the 1996 census. Municipal boundaries and the latitude and longitude of municipal and village centres were also obtained from the census database. All the boundaries and urban central coordinates of the 749 *municípios*[3], as well as the geographical positions of the 256 villages were georeferenced. Population estimates for villages and urban centres that had not been included in the official census data were also obtained from municipal governments in order to compare urban population values obtained from the linear regression.

The electrical power consumption data was obtained from the power companies of the states of Acre, Amapá, Amazonas, Pará, and Rondônia (80% of the region). The data set included total electrical power consumption, measured in kWh for 1999, and grouped

[3] Each state in Brazil is divided into *municípios* - a territorial area, governed by a mayor, that includes the main city, the rural area, and small settlements and villages.

according to the different activity sectors: residential, industrial, commercial, rural, public illumination, and public services.

3.2. DMSP/OLS Image processing for nighttime light foci extraction.

A stable nighttime light image mosaic covering Brazilian Amazonia was used. The mosaic was generated by NOAA- National Geophysical Data Center, from 16 single DMSP/OLS orbit, from September 2^{nd} to 18^{th}, 1999. Nighttime passes of the DMSP typically occured between 8:30 p.m. and 9:30 p.m. local time. To have only stable light sources in the final image, ephemeral nighttime light like clouds and fires were removed during the mosaic process, using the procedure described by Elvidge et al. (1997a). The original image data were available in an Equidistant Cylindrical projection with cells that were 0.008333 degrees square, or 1 km^2 approximately. The conversion to Polyconic projection was the only geometrical correction applied to the image. Although the DMSP/OLS image used an 8-bits quantization (256 values), its histogram had only frequencies from 7 to 100, related to the percentage of lighted pixels. This was because the digital numbers in the image represented the cumulative percentage of lighted pixels, considering the nighttime cloud screen orbits available and not the reflectance values.

The next processing step was to select a threshold for the pixel values that would be able to detect urban areas without overestimating larger cities or underestimating small villages. The binary images obtained by applying different threshold values were comparable to the DMSP/OLS data, using the location of small towns and big cities in the TM/LANDSAT image as a reference. To preserve the city boundaries and to detect small towns for the continental US, Imhoff et al. (1997) used a threshold value of 89%. It was found that a threshold of 7% overestimated the city boundaries, and a threshold of 89% did not detect most of the small towns. As a compromise, a threshold of 30% was defined to generate a DMSP binary image with two values, assigned to the classes of background and lighted pixels. Thus, the image was converted into boundaries, extracting polygons of nighttime light area, hereafter called nighttime light foci. As a result, both the image and boundary (polygons) representations of the nighttime light areas were available in the database.

3.3. Data Integration and Analysis

The process of data integration and analysis is depicted in. Figure 1. First, to verify the relation of DMSP/OLS data with urban settlements and human activity in Amazonia, the boundaries of the nighttime light foci were compared with the geographical coordinates of IBGE urban centres and villages. Using spatial query tools, all the *municípios* that did not contain any nighttime light focus were retrieved. Similarly, all the night light foci that were less than 5 km from the urban centres and villages were obtained. Next, all the nighttime light foci that did not correspond to any IBGE data were reviewed by overlaying the nighttime light boundaries on the auxiliary image data (LANDSAT and JERS). This procedure identified all the human activities detected by DMSP nighttime lights that were unrelated to census data (position of urban centres and villages).

To explore the relations between DMSP/OLS nighttime light and the human population, and between DMSP/OLS nighttime light and electrical power consumption, a linear regression procedure was applied.

4. Results

4.1. Agreement between DMSP/OLS nighttime lights and human activity/urban sites in Amazonia

By visualizing the DMSP nighttime light foci with the city centres and *villages* overlaid, it was possible to verify the capability of the DMSP/OLS data to detect human activity. Given a DMSP image threshold of DN>30, 261 nighttime light foci were detected, while with DN>7, it was possible to identify 560 foci. Even without any specific geometrical correction, the visual analysis verified a satisfactory agreement between the nighttime light foci and the spatial representation of the IBGE urban centres, as presented in Figure 2.

From the total of 261 nighttime light foci, 149 contained IBGE urban centres and 64 were less than 5 km from IBGE urban centres. There were 48 nighttime light foci that were not related to any urban centre. These 48 foci were analysed using the ancillary data from "*Mosaico do Brasil*". The results, summarized in Table 1, indicated that DMSP nighttime light detection was closely related to human activity. Even in places without a resident population, the lights indicated human presence that required some type of infrastructure, such as mining or gas production. All the 16 urban centres that had a wrong geographical coordinate from IBGE were corrected in the database. They were positioned correctly based on the night light foci and the TM/LANDSAT images. Small towns, villages and other urban nuclei were not considered for further analysis; instead, some of them were used to evaluate the linear regression proposed.

Of the 749 *municípios* analysed within the state boundaries of Amazonia, 186 were found inside the nighttime light foci and 62 were less than 5 km from the foci, for a total of 248 cities detected by the DMSP/OLS data. Considering the total resident population (Table 2), DMSP/OLS imagery could, in some cases, detect the nighttime light from *municípios* with populations of up to 2,000 inhabitants. However, DMSP/OLS nighttime light detected all *municípios* only in the population class of more than 100,000 residents. *Municípios* with populations between 50,000 and 100,000 were only partially detected.

There were 501 towns that could not be detected by DMSP nighttime light. Santa Luzia do Maranhão was the undetected *município* with the highest total population (53,287 people of which 19,450 were urban population); the lack of TM/LANDSAT images for 1999 and 1997 mosaics related to this area indicated frequent cloud cover. Alta Floresta (MT) had the highest urban population (35,053 people), and it was detected only with the DMSP image threshold of DN=7, probably due to very intense fires and smoke in this region at the time the satellite images were taken, attenuating the nighttime light signal. Only 25 of the 501 undetected towns had urban populations greater than 10,000 people. With the exception of Alta Floresta and Rosário do Oeste, located in the state of Mato Grosso, all of them were in the northern part of the states of Acre, Amapá, Pará, and Maranhão, where cloud cover is very frequent.

Among the 248 towns detected by DMSP nighttime light, Paço do Lumiar (MA) presented the smallest urban population (1095), but it is adjacent to São José do Ribamar and São Luís, the capital of the state of Maranhão, and is thus, part of a metropolitan region. The city detected by DMSP nighttime light with the smallest urban population was Alto Alegre (RR), with 3,292 people within the city limits. The population limit to be detected by DMSP nighttime light depends on the extent to which lighting is used, which is highly dependent on economic factors, as described by Elvidge et al. (2001).

4.2. Relations between DMSP/OLS nighttime lights and urban population estimates

Given that in Amazonia 60% of the population lives in urban areas, and that the DMSP/OLS data registers nighttime light with a spatial resolution of $1km^2$, the comparison between DMSP/OLS nighttime light and population was restricted to the urban population data.

Plotting the population for each *município* against DMSP nighttime light area (Figure 3) for the Amazonia region, the dispersion of the DMSP nighttime light area for *municípios* with less than 250,000, and the saturation of the DMSP nighttime light area for *municípios* with more than 400,000 urban populations was observed. The saturation of the DMSP nighttime light area can be explained by the human concentration in urban centres and the consequent process of vertical densification, observed in cities with more than 400,000 people, which correspond to the capitals of the states of Amazonia.

To assess accuracy, data analysis was restricted to the state of Pará, thus reducing data variability and heterogeneity. Pará has 1,249,460 km^2 and is a representative sample both in terms of area, approximately 25% of the Amazonia region, and in terms of land use complexity in which deforestation, mining, timber exploration, forest reserves, conservation units, agriculture, pasture, urban areas, etc. are commonly encountered. From a total of 142 *municípios*, 54 had nighttime lights detected by DMSP imagery. The relation between urban population and DMSP nighttime light area is presented in Figure 4, excluding the city of Belém - the capital of the state with more than 1,000,000 people. The general aspect obtained for the Amazonia region was preserved for the state of Pará. However, the extreme points of the dispersion indicated two groups of outliers: *municípios* where DMSP nighttime light area was greater than the population and *municípios* where the population was higher than the DMSP nighttime light area predicted. The first group is comprised of the *municípios* of Barcarena on the river edge, Oriximiná, Paragominas, and Parauapebas, cities with wide areas of mining or strip mining that are illuminated 24hs a day. Breves, Cametá and Abaetetuba comprise the second group: these urban settlements are sprawled along the riverside ("população ribeirinha"), as shown in the TM/LANDSAT image. These *municípios* with special characteristics were considered outliers and discarded from the data set. Using the resulting *municípios*, a linear relation could be observed between urban population and DMSP nighttime light area for the state of Pará (Figure 5) with a coefficient of determination (R^2) equal to 0.79. This result is compatible with that obtained by Elvidge et al. (1997b), that had a $R^2 = 0.85$ in a log-log relation of population and DMSP lit area, considering 21 countries on a global scale.

The linear regression model obtained was used to estimate the population of other urban sites detected by the DMSP nighttime light in the Amazonia region, whose population values were unavailable at the time of the IBGE 1996 census. The urban population estimated by the regression was then compared to estimates provided by the mayor's office of the respective *município.* Some of the results are presented in Table 3. Some noteworthy cases are described below.

For the village of Mosqueiro in the state of Pará, the regression estimated a value of 72,388 for its population. However, as Mosqueiro is on the river edge, the light reflected by the river is captured by the DMSP sensor, a situation which is referred to as the "blooming" effect, depicted in Figure 6. To account for this effect, the population estimate from DMSP night-lights for Mosqueiro was obtained by taking half of the city's observed value. Applying this correction factor, the estimate drops to 34,808 people, which is comparable to the field information of approximately 30,000 people.

For the município of Parauapebas, in the state of Pará, the total of DMSP nighttime light area estimated a population of 144,200 people, but this value was related to 3 nighttime light foci, illustrated in Figure 7:

(1) The nighttime light focus estimated 48,690 people for the urban area within the city limits and it had 45,649 people;

(2) The nighttime light focus estimated 81,260 people for the village of Serra dos Carajás and the iron mine. The village was built to support 70,000 people but even though the mining region is illuminated 24hs a day, there are no permanent residents;

(3) The nighttime light focus estimated 6,939 people for the gold mining area, but there are no permanent residents at the mine.

For the village of Tucuruí, in the state of Pará, the regression estimated 16,123 people. The field data revealed 14,000 people living in the village, and the additional fact that some adjacent civil construction activities are requiring very powerful illumination. This certainly contributed to the population overestimation based on DMSP nighttime light.

These results suggested that the linear regression was a reasonable model to estimate population based on DMSP nighttime light, even using data from a region – the state of Pará, and applying it to the whole Amazonia region. Some particular nighttime light foci must be dealt with separately, like the urban areas along the river edge and the activities that demand intense illumination such as the mining and civil construction detected in this study.

4.3. Relations between DMSP/OLS nighttime lights and Electrical Power Consumption

The relations between the DMSP nighttime light areas and electrical power consumption for the state of Pará were also studied. To start, data on electrical power consumption was obtained from the state's power company, according to consumer type (residential, industrial, commercial, rural, public illumination, and public services). A linear relation ($R^2 = 0.91$) was found between population and non-industrial electric power consumption.

Thus, it was conjectured that the DMSP nighttime light were related to non-industrial lights such as public illumination, roads, external lights of houses, parking lots, and shopping center lighting. To verify this assumption, the relation between the DMSP nighttime light area and the electrical power consumption for public illumination and commerce was determined (Figure 9). Residential electrical power consumption was excluded from this analysis because the external use of electricity for houses is negligible compared to public illumination and commercial use.

At first glance, the relation between DMSP and electrical power consumption showed a high dispersion, especially for those *municípios* with DMSP nighttime light areas higher than 100 pixels. However, as was mentioned in the previous section, some *municípios* had special characteristics and had to be treated as outliers and discarded from the data set. After discarding these regions, a linear relation between the electrical power consumption (public + commercial illumination) and the nighttime light pixels of DMSP imagery was observed, as shown in Figure 10 ($R^2 = 0.80$). Similarly, the total electrical power consumption could be estimated from the DMSP nighttime light, as can be seen in Figure 11, with R^2=0.79. This result compared well with the work of Elvidge et al. (1997b), who obtained a coefficient of determination of 0.96 for the relation between electrical power consumption and DMSP area lighted for 21 sampled countries. In this case, the author used aggregate data at a national level, whereas this study used a more detailed scale at a municipal level. Additionally, Sutton et al. (1997) found a correspondence between the DMSP area and urban clusters for the continental US, obtaining statistically significant results both on the linear (R^2=0.84) and exponential (R^2=0.93) models. The differences between the results found in the literature and the results obtained in this study can be attributed to the substantial economic and social differences between urban settlements in Brazil and the US, which have more equipment, infrastructure, and, consequently, more lights than the Amazonia region.

Given the substantial differences between urban settlements in Amazonia and other regions around the globe, the establishment of a positive relationship between DMSP and urban population and between DMSP data and power consumption in the region can be considered an important result. It should be noted that this result was obtained after a critical analysis of DMSP data and the removal of contagion effects and outliers.

5. Conclusions

This work explores the DMSP/OLS nighttime light imagery as a potential indicator of human presence and activity in the Amazonia region.

The DMSP nighttime light detected 248 of a total of 792 *municípios*, and every foci was shown to be related to some type of human activity (urban settlements, natural gas production, or mining and civil construction). It was possible to locate urban settlements precisely, correcting official IBGE data (geographical coordinates of urban centres) and to depict a more accurate urban population distribution in the region.

Comparing DMSP data with urban population estimates, a large variation in data dispersion for the *municípios* with less than 200,000 inhabitants was detected along with high saturation for *municípios* with more than 400,000 people. It was therefore difficult at first to establish a direct relationship between DMSP data and urban population. By reducing the data set to the *municípios* of the state of Pará and by discarding *municípios* with extreme values, a linear relationship between urban population and DMSP nighttime light area (R^2 = 0.78) was detected. Applying this relationship to urban settlements whose urban population was not available in the data set, the population estimated from DMSP data was close to the Census estimates, once the effects of contagion, river edges, and the presence of other activities like industries, civil construction and mining were taken into consideration.

In conclusion, the results indicated that DMSP nighttime light data is a consistent indicator of human activity in Amazonia. With the imagery data available, it was possible to identify all urban centres with more than 50,000 inhabitants. The constant cloud cover, the small size of the urban nuclei, and problems in the electrical power supply throughout the Amazonia region prevented a detailed estimation of urban settlements smaller than 50,000 inhabitants. Moreover, there is a linear relation between DMSP and population and DMSP and electrical power consumption. However, it is indispensable to identify and extract the outliers from the original data set. These restrictions also apply when using DMSP to estimate population and/or electrical consumption for regions with similar socio-economic and spatial patterns.

DMSP nighttime light such as those assessed in this study have a potential to be used as a reference of human activity and urban settlement, including use as assumed variables in land use and land cover change (LUCC) models. Many LUCC dynamic models are based on regressions of data aggregated by *municípios* (e.g. Andersen and Reis, 1997 and De Koning *et al*., 1998). Given the disproportionate size of Amazonian *municípios* as compared to their respective cities, projective models need to have the city limits and urban population correctly defined and spatially represented. Nighttime light maps can provide a valuable tool for this modelling process.

Any projective/predictive model of settlement processes in Amazonia must take human activity into account. Improved public services and infrastructure for both urban and rural population within the urbanization process have been positively linked to a decrease pressure on the frontier due to reduced rates of deforestation (Becker, 1998). Given the speed and dynamics of change in land cover in the region, the lack of more frequent census data, and all the strategic infrastructure programs proposed by the federal government for the Amazonia region (Governo Federal, 2000), DMSP data is essential as a reference of human activity in future analysis of spatial-temporal patterns in Amazonia.

The results from this study suggest public policy makers may refer to DMSP data as a valid indicator of actual human socio-economic activity in the Amazonia region as long as the necessary statistical constraints are applied.

Acknowledgements

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References

Alves, D. (1999). *An analysis of the geographical patterns of deforestation in Brazilian Amazônia in the 1991-1996 period.* Paper presented at 48th Annual Conference of the Center for Latin American Studies - Patterns and Processes of Land Use and Forest Change in the Amazon, University of Florida, Gainesville, 23-26 March.

Andersen, L.E.& Reis, E.J. (1997). *Deforestation, development and government policy in the Brazilian Amazon: an econometric analysis. Texto para discussão nº 513*. Rio de Janeiro: IPEA.

Becker, B. K. (1995). Undoing Myths: The Amazon - An Urbanized forest. In Clüsener, G. M., Sachs, I. (Eds.), *Brazilian Perspectives on sustainable development of the Amazon region - Man and Biosphere Series* (pp. 53-89). Paris: UNESCO e Parthenon Publish Group Limited.

Becker, B. K. (1998). *A Especificidade do Urbano na Amazônia: Desafios para políticas Públicas Consequentes. Estudo elaborado para a Secretaria de Coordenação dos Assuntos da Amazônia Legal - Ministério do Meio Ambiente*. Rio de Janeiro: Ministério do Meio Ambiente.

Browder, J.O.& Godfrey, B.J. (1997). *Rainforest Cities: Urbanization, development, and globalization of the Brazilian Amazon,* New York: Columbia University Press.

Câmara, G.; Souza, R.C.M.; Freitas, U.M.& Garrido, J.P. (1996). SPRING: Integrating Remote Sensing and GIS with Object-Oriented Data Modelling. *Computers and Graphics, 15*, 13-22.

Capobianco, J.P. (2001). *Biodiversidade na Amazônia Brasileira, avaliação e ações prioritárias para a conservação, uso sustentável e repartição de benefícios,* São Paulo: Editora Estação Liberdade e ISA.

Croft, T.A. (1973). Burning waste gas in oil fields. *Nature, 245*, 375-376.

Croft, T.A. (1978). Nighttime images of the earth from space. *Scientific America, 239*, 86-98.

De Koning, G.H.J.; Veldkamp, A; Verburg, P.H.; Kok, K.& Bergsma, A.R. (1998). *CLUE: A tool for spatially explicit and scale sensitive exploration of land use changes*. Available: http://www.gis.wau.nl/~clue/index.html.

Dobson, J.E.; Bright, E.A.; Coleman, P.R.; Duree, R.C.& Worley, B.A. (2000). LandScan: A Global Population Database for Estimating Populations at Risk. *Photogrammetric Engineering and Remote Sensing, 66*, 849-857.

Doll, C.N.H.; Muller, J.P.& Elvidge, C.D. (2000). Night-time Imagery as a Tool for Global Mapping of Socioeconomic Parameters and Greenhouse Gas Emissions. *AMBIO, 29*, 157-162.

Elvidge, C.D.; Baugh, K.E.; Kihn, E.A.; Kroehl, H.W.& Davis, E.R. (1997a). Mapping city lights with nighttime data from the DMSP Operational Linescan System. *Photogrammetric Engineering and Remote Sensing, 63*, 727-734.

Elvidge, C.D.; Baugh, K.E.; Kihn, E.A.; Kroehl, H.W.; Davis, E.R.& Davis, C.W. (1997b). Relation between satellite observed visible-near infrared emissions, population, economic activity and electric power consumption. *International Journal of Remote Sensing, 18*, 1373-1379.

Elvidge, C.D.; Imhojj, M.L.; Baugh, K.E.; Hobson, V.R.; Nelson, I.;Safran, J.; Dietz, J.B.& Tuttle, B.T. (2001). Night-time Lights of the World: 1994-1995. *ISPRS Journal of Photogrammetry & Remote Sensing, 56*, 81-99.

Foster, J. L. (1983). Observations of the Earth using nighttime visible imagery. *International Journal of Remote Sensing, 4*, 785-791.

Gash, J.H.C.; Nobre, C.A.; Roberts, J.M.& Victoria, R.L. (Eds.). (1996). *Amazonian Deforestation and Climate.* Chichester*:* John Wiley.

Governo Federal (2000). *Programas Estratégicos: Infra-estrutura.* Available: www.infraestruturabrasil.gov.br/estrategico/infra.asp.

IBGE (Ed.). (1995). *Pesquisa Nacional por Amostra de Domicílios - PNAD de 1995.* Rio de Janeiro*:* Ministério do Planejamento e Orçamento.

Imhoff, M.L.; Lawrence, W.T.; Elvidge, C.D.; Paul, T.; Levine, E.; Privalsky, M.V.& Brown, V. (1997). Using Nighttime DMSP/OLS Images of City Lights to Estimate the Impact of Urban Land Use on Soil Resources in the United States. *Remote Sensing of Environment, 59*, 105-117.

INPE, Instituto Nacional de Pesquisas Espaciais (2002). *Monitoramento da Floresta Amazônica Brasileira por Satélite 2000-2001.* São José dos Campos: MCT, Instituto Nacional de Pesquisas Espaciais, Governo Federal.

Monte-Mór, R.L.M. (1998). Health, the Environment and Urban-Rural Relations in Amazonia. In Chatterji, M.; Munasinghe, M.; Ganguly, R. (Eds.), *Environment and Health in Developing Countries* (pp. 149-156). New Delhi, India: A.P.H. Pub. Corporation.

Plutzar, C.; Grübler, A.; Stojanovic, V.;Riedl, L.& Pospischil, W. (2000). *A GIS-based Approach for Modeling the Spatial and Temporal Development of Night-time Lights*. Available: http://www.pph.univie.ac.at/vegoek/personal/plutzar/a2000.html.

Sutton, P.; Roberts, D.; Elvidge, C.D.& Meij, H. (1997). A comparison of Nighttime Satellite Imagery and Population Density for the Continental United States. *Photogrammetric Engineering and Remote Sensing, 64*, 1303-1313.

Welch, R. (1980). Monitoring urban population and energy utilization patterns from satellite data. *Remote Sensing of Environment, 9*, 1-9.

Welch, R.& Zupko, S. (1980). Urbanized area energy patterns from DMSP data. *Photogrammetric Engineering and Remote Sensing, 46*, 201-207.

FIGURES

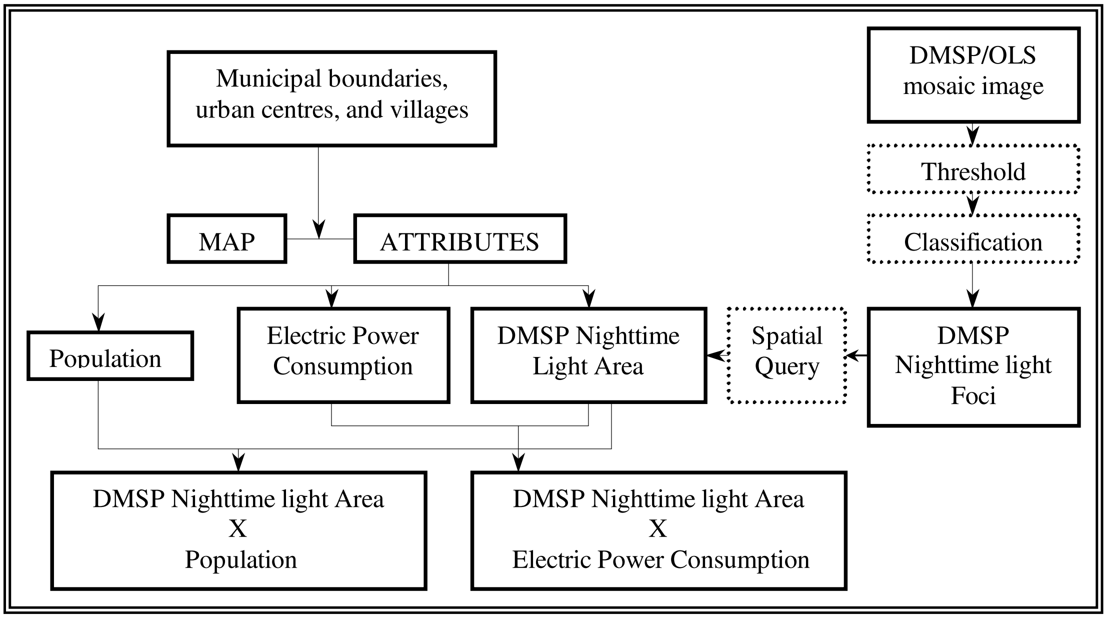

Fig 1. General methodology - data integration and analysis flow-chart.

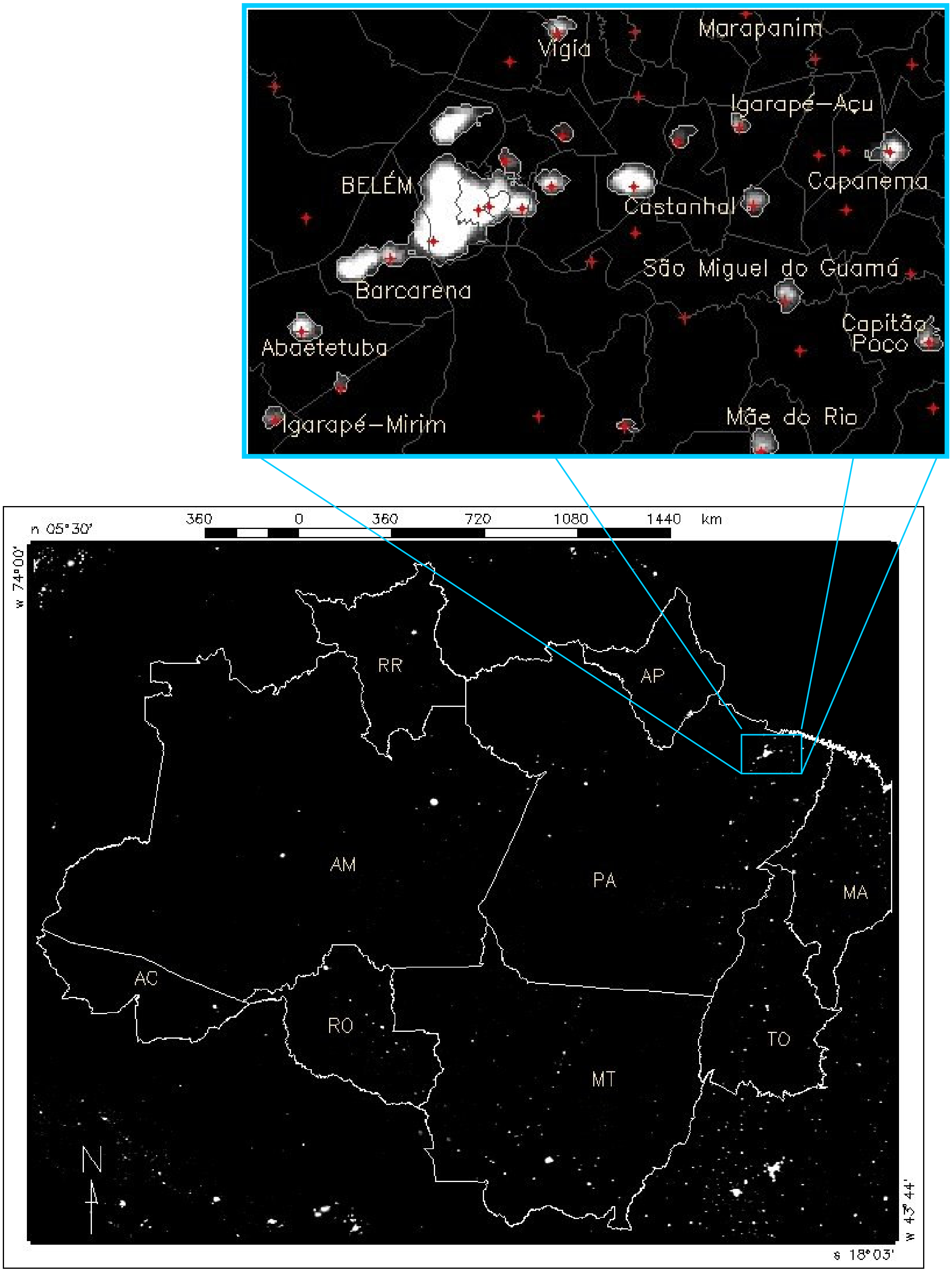

Fig. 2. DMSP/OLS nighttime light image over Amazonia. In detail: Belém metropolitan region, state of Pará.

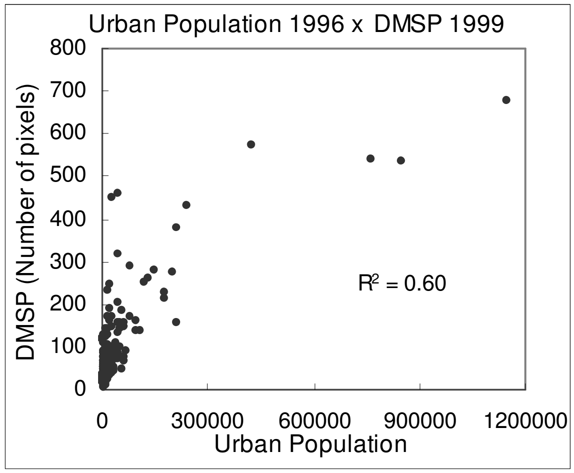

Fig. 3. DMSP nighttime light area for 1999 plotted against the urban population (1996) for all the *municípios* in the Amazonia region.

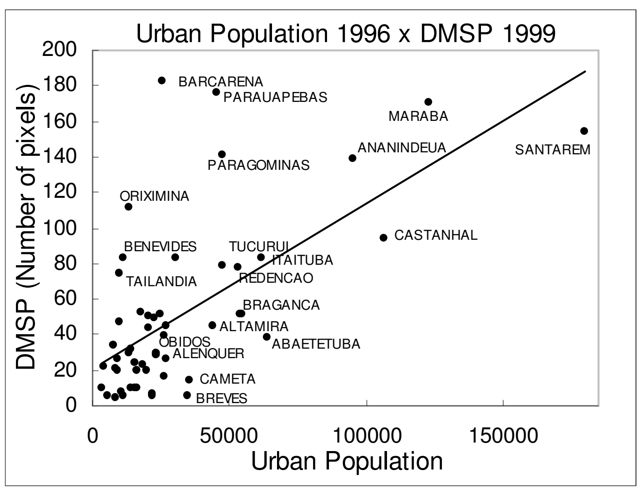

Fig. 4. DMSP nighttime light area plotted against the urban population (IBGE-1996) for *municípios* of the state of Pará, excluding Belém, the capital.

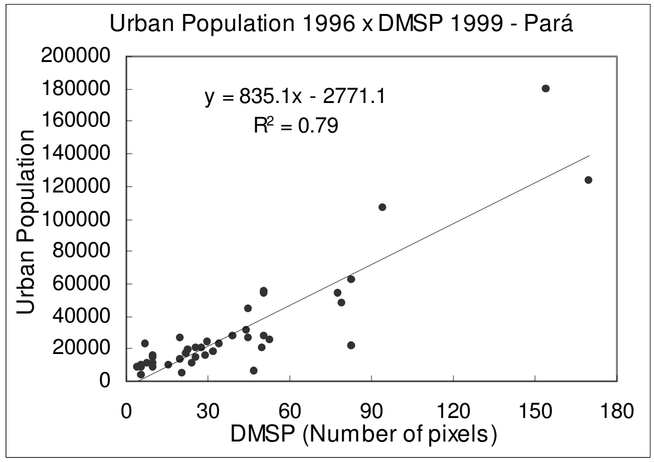

Fig. 5. Linear relation between DMSP nighttime light area and the urban population for *municípios* of the state of Pará.

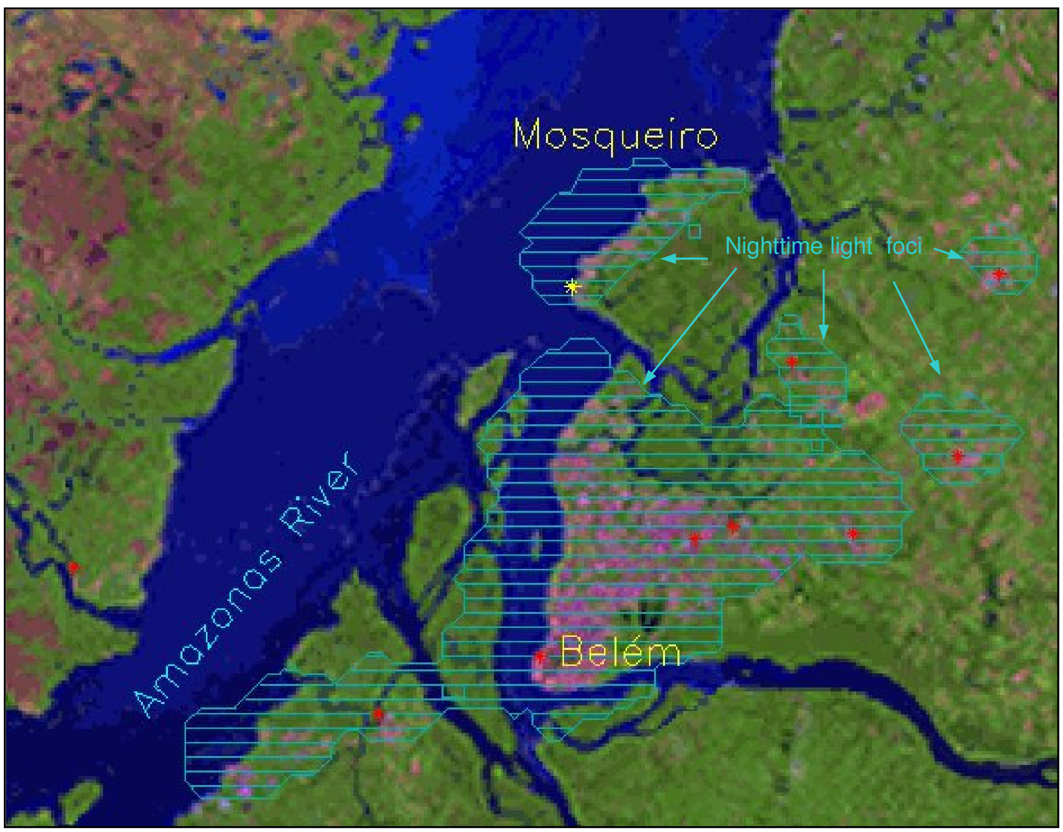

Fig. 6. The "blooming" effect of DMSP nighttime light at Mosqueiro/Belém region. Polygons of nighttime light foci over TM/LANDSAT colour composition image.

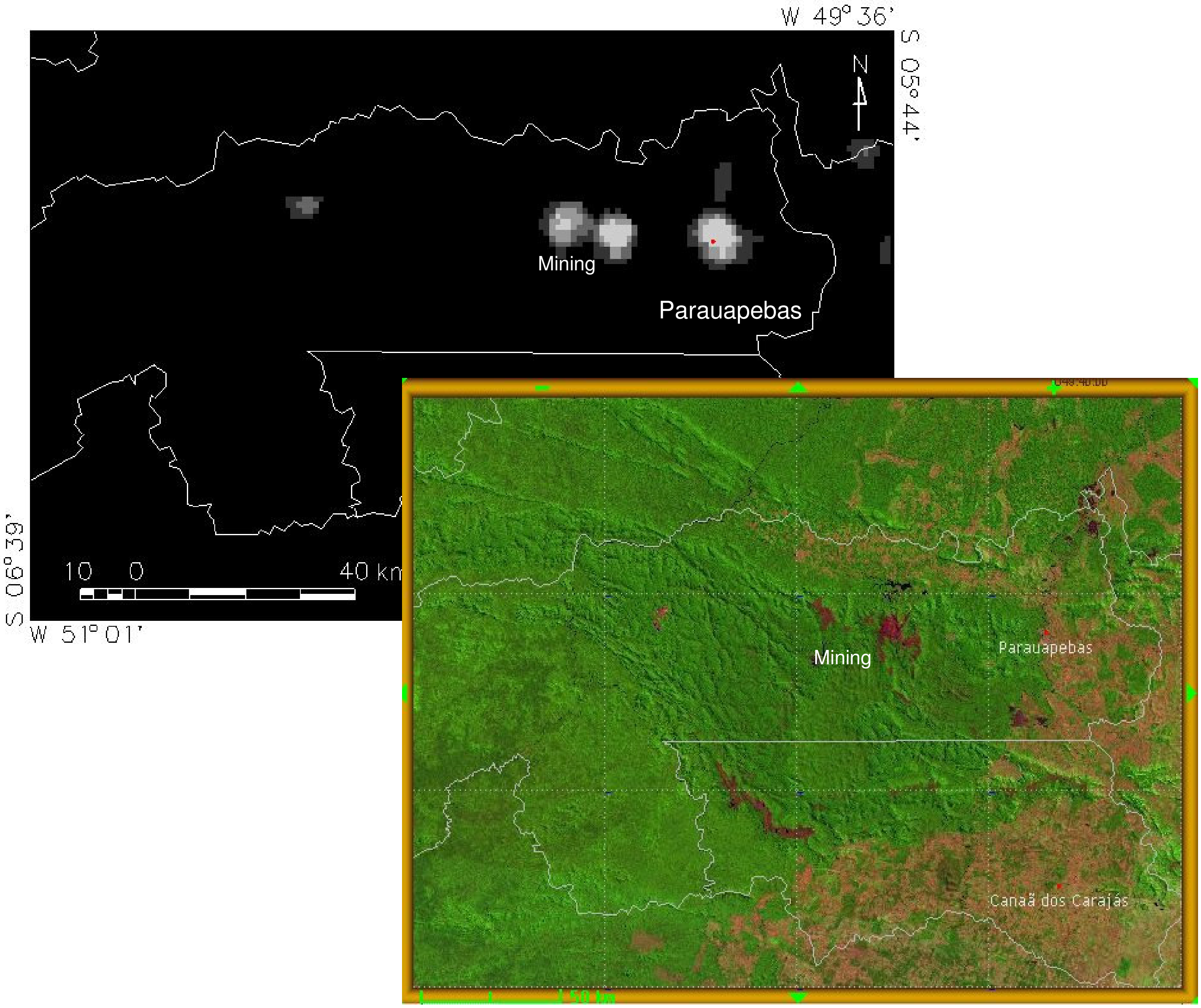

Fig. 7. DMSP nighttime light and TM/LANDSAT colour composition images related to *município* of Parauapebas, state of Pará.

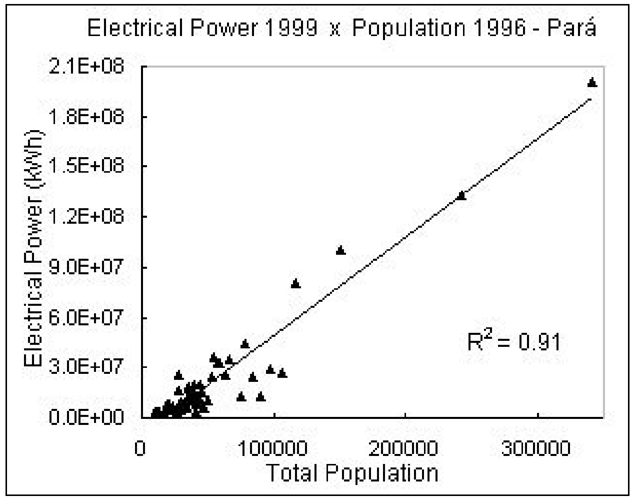

Fig. 8. Electrical Power consumption for 1999 (kWh) and Total Population (1996) for all *municípios* of the state of Pará, excluding Belém, the capital.

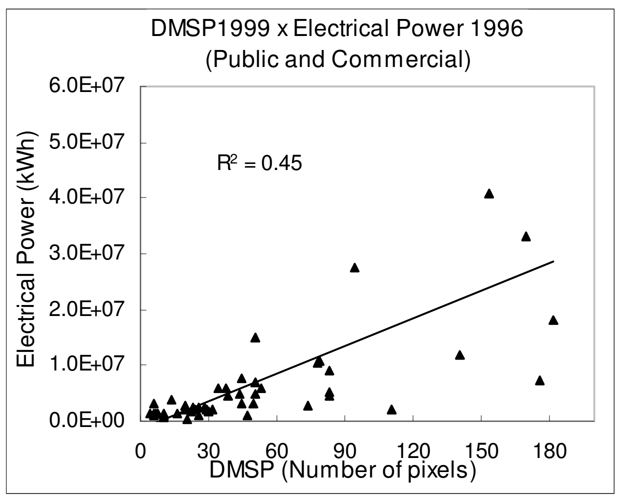

Fig. 9. DMSP nighttime light area and the Electrical Power Consumption for Public and Commercial sectors at 1999 (kWh) for all the *municípios* of the state of Pará, excluding Belém.

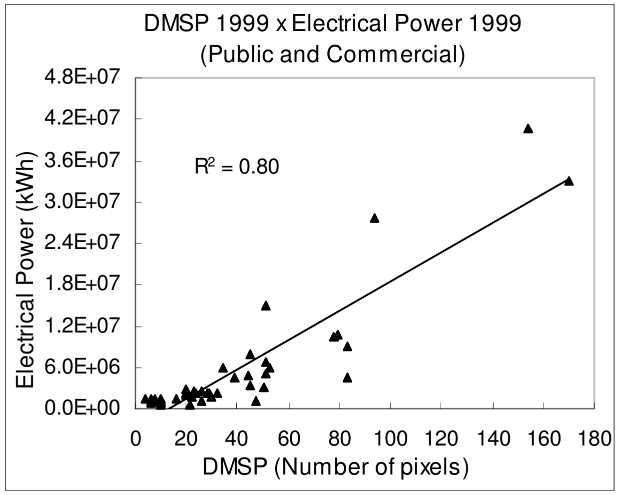

Fig. 10. DMSP nighttime light area and the Electrical Power Consumption for Public and Commercial sectors at 1999 (kWh) for state of Pará without outliers.

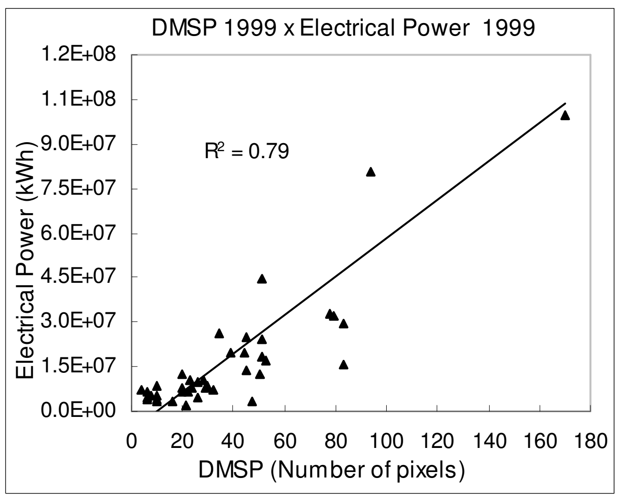

Fig. 11. DMSP nighttime light area and the Total Electrical Power Consumption (kWh) -1999 for state of Pará, without outliers.

TABLES

Table 1

DMSP nighttime-light foci not associated with urban centres

Description - targets observed in "Mosaico do Brasil"	N° of DMSP Foci
Urban settlements - small towns and villages - missing in IBGE census	9
IBGE Villages	3
Urban nuclei near big cities	4
Villages near reservoirs	2
Mining	3
Oil and Gas production (URUCU-AM)	1
IBGE urban centres - inaccurate coordinates	16
Unable to check - TM/LANDSAT or JERS images not available	7
Outside of Amazonia limits	3

Table 2

Frequency of *municípios* in the Amazonia region for each class of population

Total Population	**Number of *Municípios***	
(IBGE-1996)	**Total**	**Detected by DMSP**
0 - 2,000	32	1
2,000 - 5,000	133	5
5,000 -10,000	180	28
10,000 -20,000	206	67
20,000 -50,000	145	96
50,000 - 100,000	36	34
100,000 - 200,000	7	7
200,000 -500,000	7	7
500,000 - 1,000,000	1	1
>1,000,000	2	2
Total	**749**	**248**

Table 3

Urban population estimated by the linear relation with DMSP nighttime light and verified through field information

Site – state	**Urban Population**	
	Estimated	**Verified**
Lourenço – Amapá	1100	1203
Mosqueiro – Pará	72388	34808
Parauapebas – Pará		
Urban centre	48690	45649
Village	70000	81260
Oriximiná – Pará		
Urban centre	23638	23540
Village	26979	6500
Tucuruí – Pará	16123	14000