DMSP/OLS night-time lights imagery and urban population estimates in the Brazilian Amazon

S. AMARAL [a], A. M. V. MONTEIRO [a], G. CAMARA[a] and
J. A. QUINTANILHA[b]

[a] Instituto Nacional de Pesquisas Espaciais (INPE), Divisão de Processamento de Imagens (DPI), C.P. 515, São José dos Campos, São Paulo, 12210-970, Brazil

[b] Escola Politécnica da Universidade de São Paulo (POLI-USP), Av. Almeida Prado, Trav. 2, nº 83, São Paulo, São Paulo, 05508-900, Brazil

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1. Introduction

The Brazilian Amazon occupies 5 million km² and comprehends the largest preserved and continuous tropical rain forest in the world: a forested area of approximately 4 million km². In the last decades, the region has experimented intense transformation processes both in the physical and human aspects. Deforestation studies estimated a rate of 25 400 km² of forest conversion for 2001 to 2002 period (INPE 2003). At the same time, the Legal Amazon[1] in 2000 official census totalled 21.1 million of inhabitants, contributing with 12.4% for the total of the Brazilian population, in contrast with the contribution of 5.8% in 1950 (SUDAM/PNUD 2001).

The importance and the extension of the Amazon forest for the dynamic of climatic and biogeochemical processes makes the Amazon deforestation a frequent study subject, specially considering the carbon cycling, the global climatic and environmental changes (Potter *et al.* 2001, LBA 2003, Roberts *et al.* 2003, Durieux *et al.* 2003, Ballester *et al.* 2003), and the biodiversity conservation (Fearnside 2001). The human dimension and its aspects are partially neglected. Human density, as an example, is usually indicated as one of a series of variables to explain the deforestation process (Geist and Lambin 2001, Wood and Skole 1998).

[1] The Brazilian Legal Amazônia comprehends all the states of the north region (Amazonas, Pará, Acre, Rondônia, Roraima, and Amapá), the states of Mato Grosso, Tocantins and part of the state of Maranhão.

The pattern of the human population growth in the Amazonia region was similar to the Brazilian population in the urban and in the rural areas, and included an intense urbanization process. In 1970, the urban population corresponded to 35.5% of the total population in the region. This value arose to 58% in 1991 and reached 69% in 2000 (IBGE 2001). The diversification of the economic activities and the changes in the population network reorganised the human settlements structure, leading to the term "urbanized forest" to designate the Amazon region (Becker 1998).

In contrast to the conservation aspect, a relatively small number of researchers are concentrating on the human aspects of the Amazonian occupation. These studies had shown that the growth in urban population has not came with an improvement on quality of life of local populations, as observed by the low indices of health, education and income wages (Becker 1995, and Becker 1998, Browder and Godfrey 1997, Monte-Mór 1998). The human life condition at Amazon cities and settlements can be considered one the major and worst environmental problem in the region (Becker 2001).

The sustainable development of the Amazon region is a real issue, considering the physical and human demands, and it is an actual challenge for the world science. At this ambit, remote sensing data and techniques have contributed significantly to integrate the physical and human dimensions, where the objective is to understand the land cover/land use change in the Amazon region (Frohn *et al.* 1996, Wood and Skole 1998). Demographical concepts and methods have also used remote sensing to explain different land use/cover patterns, but at household scale, and for local changes (Moran *et al.* 1994, Moran and Brondizio 1998, McCracken *et al.* 1999, Moran *et al.* 2003).

For modelling purpose, at regional scale, information characterizing the human population and distribution is scarce. Demographical data are restricted to the decennial census, and some annual estimates based on statistics (PNADs) for some metropolitan regions, that do not cover the whole Legal Amazon. Remote sensing data, especially from the night-time lights imagery has been pointed out as an alternative source of information to identify urban settlements, and indirectly, to characterize the human population distribution (Sutton *et al* 1997, Elvidge *et al* 1997).

Using night-time lights imagery from the Defense Meteorological Satellite Program / Operational Linescan System (DMSP/OLS) in the Amazon region, it was possible to efficiently detect the human presence, such as urban settlements and light demanding activities, as mining civil construction (Amaral *et al.* 2003). Additionally, electrical power consumption, urban area extension, and urban population presented linearly related to the DMSP night-time lights. The authors suggested that DMSP night-time lights imagery generated from a more representative time series would more precisely represent the urban population distribution.

This article assesses DMSP/OLS night-time imagery as information source to detect human settlements and to estimate the urban population in the Amazon region. To reach this goal, recent DMSP/OLS single orbits were used to generate new DMSP stable lights mosaics. These mosaics were integrated to the census data and a comparative procedure enabled the investigation of correlation between DMSP/OLS night-lights and the urban population data and statistical projections. The final objective was to identify the potentials and the restrictions in estimating urban population through DMSP night-time lights as an alternative to annuallly monitor the urban population dynamic in a region where field work is very costly, and the census data is scarce.

2. The DMSP/OLS and human activity detection

The U.S. Air Force Defense Meteorological Satellite Program (DMSP) has been in operation since the 1970s. The Operational Linescan System (OLS), onboard of the DMSP satellites, is an oscillating scan radiometer capable of detecting visible and thermal-infrared emissions witch was originally developed for global meteorological forecasting for the US Air Force. Using a photo multiplier tube (PMT) at night, the visible spectral band (0.47 - 0.95 μm) makes the sensor very sensitive to faint visible and near-infrared (VNIR) emission sources (Elvidge *et al.* 1997b) such as those produced by the night-time light of cities, towns, fires, lightning, etc. 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 high contrast between lighted and unlighted areas and the sensor's spatial resolution makes it a useful tool to identify regions of intense human activity (Croft 1973, 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 National Oceanic and Atmospheric Administration's (NOAA), National Geoscience Data Center (NGDC) developed a methodology to generate stable light datasets that solved the problem with ephemeral lights and cloud cover. This method includes the collection, rectification, and aggregation of a large number of night-time 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 to determine the location of all VNIR emissions (Elvidge *et al.* 1997b). The result is an image whose values are percentages of night-time light occurrences for each pixel. Elvidge *et al.* (1997a) mapped the U.S. cities in 1 km resolution cells, obtained form the occurrence of night-time lights of at least 10% of cloud free observation (from a total of 236 DMSP/OLS images). The city boundaries were enlarged what was attributed to the effects of pixel geolocation, light detected at sub-pixel scale, and the presence of fog or sparse clouds.

To restrict the urban area mapping using the night-time lights image Imhoff *et al.* (1997a) suggested an algorithm of spatial integrity threshold to reduce the pixel blooming and saturation. The process consists in identifying the lowest threshold value in the urban/not urban classification that maintains the urban core as a unit. At this case, only pixels detected as night-time lights within 89 to 100% from the total of the images were considered as urban areas. Compared to the urban areas from the 1990 U.S. Census, the urban area from DMSP night-time light was only 5% smaller. Using the same dataset and procedures, Imhoff, *et al.* (1997b) observed that 2.67% of the U.S. extension was classified as urban area, and it is placed mostly at soils type of high agricultural productivity potential. These results signalised the potential use of DMSP night-time light images for global studies of urbanization, population, and even productivity.

DMSP night-time light were also explored regarding to human population density relations. Sutton *et al.* (1997) has obtained a quantitative relationship between the intensity of DMSP night-time light (not the percentage of night-time light occurrence for a cloud free pixel) and the population density for cities of the continental United States. Urban areas densely populated presented pixels saturation in the DMSP night-time light image. The linear regression between population density and DMSP night-time image produced a coefficient of determination (R^2) of 0.84. For an exponential regression, the same coefficient resulted 0.93. In general, DMSP night-time lights underestimated the population density in the urban centres and overestimated the density in suburban areas. The authors suggested the use of DMSP/OLS data not to estimate de population density, but to indicate the human activity presence as in human population distribution models, building smart interpolator at global scales. Sutton (1997) attempted to model the population density inside urban nuclei having DMSP night-time light intensity as the reference of the urban area, using different decay functions. Urban density models were parameterized from the size and shape of the urban nuclei and from the log-log relation between the urban area and population density obtained from Sutton *et al.* (1997).

DMSP night-time light was also suggested as a feasible alternative to identify urban settlements on a global scale (Elvidge *et al.* 2001). Lighted areas were correlated with population, gross domestic product, and energy consumption of 21 countries with different economies. Linear relation with population produces R^2= 0.85, where the outliers were countries with poor economies. Similarly, electrical power consumption and gross domestic product result R^2 = 0.96 and R^2 = 0.97, respectively. These results suggested that DMSP/OLS imagery could be used to infer the global population spatial distribution, with a proper regional or national calibration. Doll *et al.* (2000) have observed that night-time light data were 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 have also been used as indicator variable of spatial distribution of the human activity in simulation models. Plutzar *et al.* 2000, using the gravitational model of spatial interactions, variables like accessibility and population density, geographical information system, simulated some patterns of night-time lights evolution as a reference of socioeconomic activities evolution in China. The authors emphasized the applicability of DMSP/OLS data as ancillary tool for planning the infrastructure and the electrical power demand in regional scale.

DMSP/OLS data have been indicated as a valuable information source to distribute the population into density surfaces (Turner and Openshaw 2001). Considering worldwide population database, DMSP/OLS data have been used to estimate population at risk as in the LandScan Project (Dobson *et al.* 2000). The distribution of the population in the LandScan project represents an ambient population that joints diurnal movements and collective travel habits in a single measure. DMSP night-time light, associated with road proximity, slope, and land cover, defined the probability coefficients that assigned census available counts in a population density surface for the entire world.

Considering its nature and the spatial resolution, the DMSP night-time light is the most suitable data source to represent the urban concentration and extension at continental and global scales (Elvidge *et al.* 2001a). The evaluation of the development level for the largest hydrographic watersheds in the word, presented by The Word Resources Institute (Revenga *et al.* 1998), is an example of the DMSP night-time light use at global scale.

At regional scale, DMSP/OLS data were recently evaluated considering the human presence and human activities in the Brazilian Amazonia (Amaral *et al.* 2003). DMSP night-time light was related to human presence and activity in the region. It was obtained a linear relation (R^2= 0.79) between urban population from the Census data and DMSP night-time light for the state of Pará, Brazil. Similarly, electrical power consumption was linearly correlated with DMSP night-time light foci. Thus the DMSP/OLS data could be used as an indicator of human presence in the analysis of spatial-temporal patterns in the Amazonian region.

3. Data and methods

3.1. DMSP/OLS night-time light mosaic images

For the analysis presented at this work, two DMSP night-time light mosaic image were provided by the NGDC/NOAA, referring to the period of 1994-95 and 1999, and two more recent mosaic image were generated, referring to 2002 and 2003. The following paragraphs describe the characteristics and procedures of the DMSP mosaics for 2002 and 2003.

The DMSP 2003 and 2003 mosaic image resulted from the mosaic of 61 DMSP/OLS night-time light images obtained from the new moon period from January to June. This period corresponds to the dry season, and consequently less cloud cover, in the Amazonia region. All the night-time light single pass images were obtained by the DMSP/F15 satellite, received by the Air Force Weather Agency (AFWA), and recorded by the National Geophysical Data Center's Solar Terrestrial Physics Division (NGDC/STP). This database was accessed and pre-processed by the *Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis* (IBAMA). The pre-processing consisted of geolocation and stable lights detection procedures, developed by NGDC for fire monitoring (Elvidge *et al.* 2001). The VNIR emission sources and clouds pixels were geolocated and identified in a reference grid, generated to each orbit. The digital number (DN) of these grids represented the occurrence of clouds, night-time lights, and glare (table 1) in each geolocated pixels for each single pass image, therefore these grids were called flag images.

Table 1. Digital number and pixel occurrence in the flag images.

DN	Flag
0	No cloud and no light
1	Cloud
2	Light
3	Cloud and light
4	Glare
5	Cloud
255	Bad Value

The flag images were then used to compute the frequency of night-time lights, free of cloud occurrence (DN 2 in the flag image), in every pixel of the grid. Similarly, the occurrence of cloud coverage free pixels was counted (DN 0 and 2 in the flag image), and the total frequency of both, light and cloud coverage free pixels, produced two new grids: a cloud coverage frequency image and a night-time lights frequency image. The total light frequency was then divided by the total free of cloud observation for the analysed period and multiplied by 100. The result was the percentage of VNIR detected for each grid cell, only considering the free of cloud coverage OLS records (Elvidge *et al.* 1997a), constituting the night-time light mosaic image.

The presence of low DN values, indicating low percentage of lights occurrences at DMSP mosaic, gives a noisy aspect to the image. Considering previous analysis about the percentage and thresholds (Imhoff *et al.* 1997, Amaral *et al.* 2003), DN lower than 30 were removed from the mosaic image. This represented a satisfactory compromise between the night-time light related to human presence, such as the municipal centres, and the isolated pixel that can be considered as noise since they can not be related to any human activity of interest (e.g. they can be vegetation fires) for the Amazonia region.

Even tough the single DMSP/OLS single orbits used for the mosaic were related to a period of officially low vegetation fire incidence in the Amazonia region, some intense fire activities were registered as night-time light. To remove this features from the DMSP mosaic images, the Database Vegetation Fires (http://www.dpi.inpe.br/proarco/bdqueimadas/) were consulted, and semi-automatic edition were performed over the DMSP mosaic images. The absence of ephemeral night-time light as vegetation fires is essential for the proper use of the DMSP mosaic images to explore the relations with population and human activity in the Amazonia region.

3.2. DMSP mosaics and urban population analysis

First, in order to assess the DMSP mosaic images as related to urban area, auxiliary data were added to the database, using Geographical Information System facilities. The geographical coordinates of the urban centres, or districts, provided by the Brazilian Institute of National Statistics and Geography (IBGE), were overlaid as point data reference. Remote sensing images available at *Mosaico do Brasil* (MCT 2003) supplied land cover information from higher spatial resolution sensors (Landsat TM and JERS images) to inform about night-time light regions not related to any urban centres.

Every pixel with DN greater than 30 (or 30%) were classified as night-time light at DMSP-2002 image. From this classified image, polygons were delimited as night-time light foci, and a buffer zone of 4 km from the foci limits outlined the unit of analysis for this study. A unit of analysis (UA) determined a zone inside witch any human activity that emitted night-time light can be detected This strategy eliminated problems with image or data registration that could be present between DMSP mosaic images (for 1995, 1999, 2002, and 2003), and even with point data of the urban centres. For every unit of analysis it was computed the total number of DMSP night-timer light pixels with DN greater than 30 for DMSP-1995, DMSP-1999, DMSP-2002, and DMSP-2003 mosaic images. Then, the urban population count for all districts that were located inside of each UA was summed, considering the IBGE census of 1996 and 2000. Finally, regression analyses were performed considering the night-time light area and the urban population estimates for the unit of the analysis, as presented in figure 1. The linear regression analyses explored the relations between DMSP-1995 with urban population 1996 and DMSP-1999 with urban population 2000.

Then, considering the equation resulted from the linear regression for DMSP-1999, the urban population was estimated for DMSP-2002 and DMSP-2003. These results were compared to urban population projection for 2001 and 2002 respectively. These population projections were published by IBGE (2003), which were based on previous inter-census growth rates tendency (IBGE 2002). As DMSP images were researched considering the census data available for the previous year, the same time lag was maintained for the analysis of the population estimates.

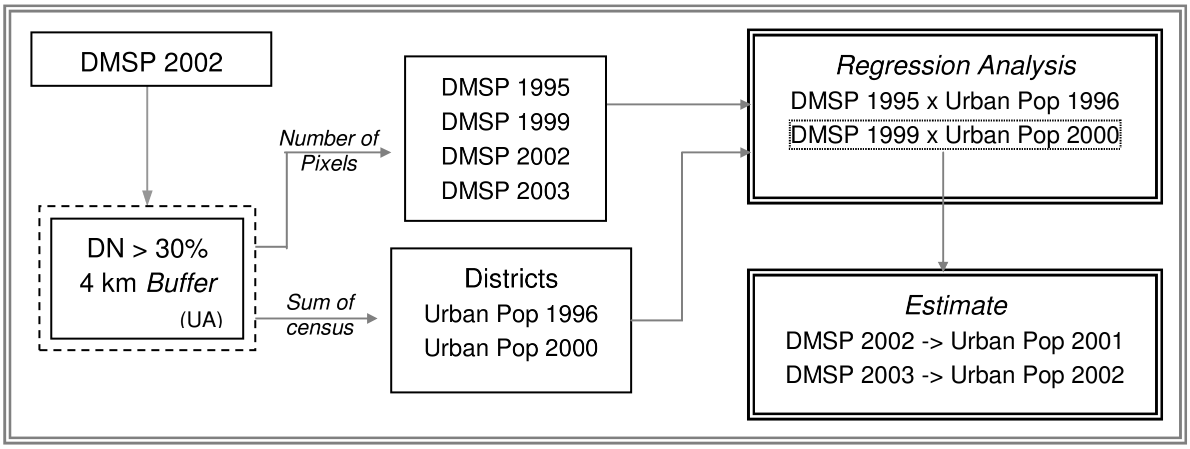
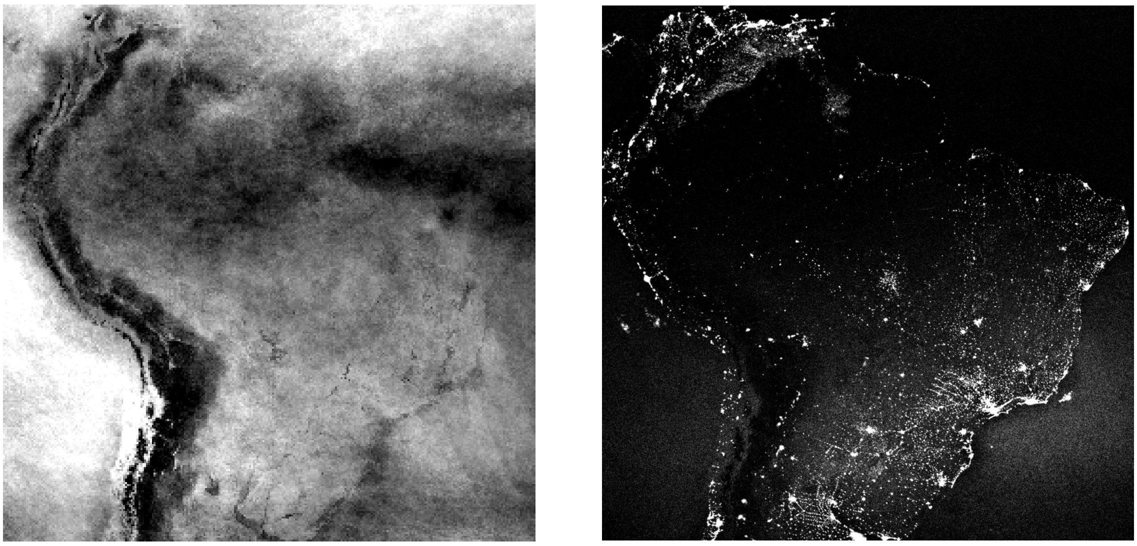


Figure 1. Methodology procedure to explore DMSP night-time lights and urban population relations.

4. Results

4.1. DMSP/OLS and urban nuclei

Figure 2 presents the DMSP-2002 image and the cloud cover frequency image, used to compute the night-time light percent, the DN pixel value for the DMSP-2002.



(a) (b)

Figure 2. Cloud cover frequency image (a), and night-time light 2002 mosaic image (b) – DN refers to the percentage of night-time light detected for the total cloud cover free pixel.

Even tough the Amazonia was one of the most intense cloud cover region, represented by the dark pixels at figure 2(a), it was possible to compare the night-time light foci and the geographical coordinates of the districts. Considering the urban population obtained for each districts in the 2000 IBGE Census the following was observed:

- 100% of the districts with urban population higher than 20 000 inhabitants (112 districts) were located inside of a unit of analysis (UA);
- From the total of 110 districts with urban population between 10 000 and 20 000 inhabitants, only 5 districts were not inside an UA. Arame (urban population of 11 461 inhabitants), and PioXII (urban population of 12 944 inhabitants) both in the state of Maranhão, and Breu Branco, (urban population of 15 952 inhabitants), in the state of Pará (PA), when examined at *Mosaico do Brasil* (www.dpi.inpe.br/mosaico) were districts with wrong geographical coordinates. The exact geographical coordinates were checked out at topographical maps (1:250 000 scale). At Terra Santa - PA (urban population of 10 965 inhabitants), the electrical power is provided by thermo electrical plant and so the night-time lights could be intermittent. Finally, at Viseu – PA (urban population of 11 558 inhabitants), the electrical power consumption at public illumination showed lower values (74.12 kWh) when compared to districts with similar urban population in the state (909.07 kWh), indicating reduced illumination equipments.
- From the total of 169 districts with urban population between 5 000 and 10 000 inhabitants, 82% of them were located inside a unit of analysis. Most of these districts were in the states of Pará and Maranhão in a region of high cloud cover frequency.
- From 613 districts with urban population less than 5 000 inhabitants, 35% were presented at a unit of analysis (219 districts).

Comparing to DMSP-1999 previous work analysis (Amaral, *et al.* 2003), a larger number of urban nuclei was detected by the DMSP-2002 mosaic image (575), at smaller urban population class. While DMSP-2002 were appropriate to detect urban nuclei at 5 000 to 10 000 urban population class, DMSP-1999 only detected the majority of the urban nuclei within 20 000-50 000 urban population class. The difference in the number of single orbit to generate the image mosaic, 16 images for DMSP-1999 and 61 for DMSP-2002, and the frequent cloud cover in the Amazon region explains this result.

DMSP mosaic images were compared based on the total of night-time light pixel higher than 30% computed for each unit of analysis for DMSP-1995, DMSP-1999, and

DMSP-2002. The expected enhancement of night-time light pixels over the period can be observed at figure 3. However this result has to be interpreted with caution, since the DMSP mosaic images were produced with increasing number of single orbits, what could lead to a misinterpretation of this result.

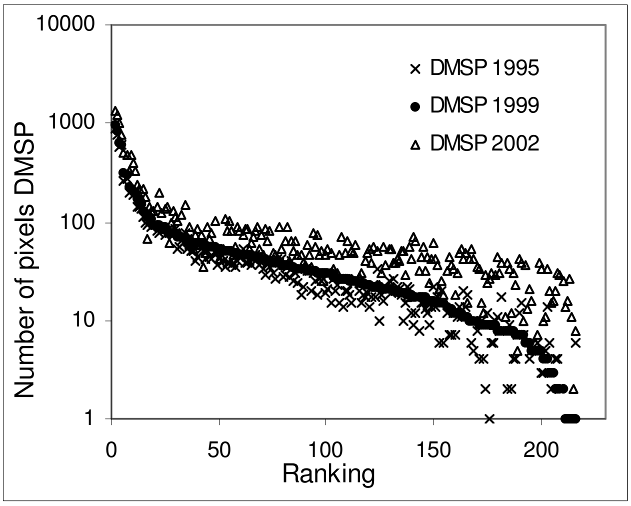


Figure 3. Number of night-time light pixels with DN higher than 30 for each unit of analysis at DMSP night-time images mosaic for 1995, 1999, and 2002.]

It was defined a total of 516 units of analysis (an 4 km buffer zone from night-time light frequency higher than 30%) from DMSP-2002 night-time light mosaic image. For DMSP-1999, a total of 280 units registered night-time light pixels, 248 of these units were related to districts with urban population. The remained 32 were related to small villages, and other locations that demands illumination but with without resident population associated, as mining and others activities.

For DMSP-1995 it was registered night-time light pixels at 243 units of analysis, from witch 226 had urban population associated, according to the IBGE 1996 Census.

4.2. DMSP and urban population estimates

Considering the total of urban population and night-time light pixels values for each unit of analysis, the linear regression analysis for DMSP-1995 with urban population 1996, and DMSP-1999 with urban population 2000 are presented in figure 4.

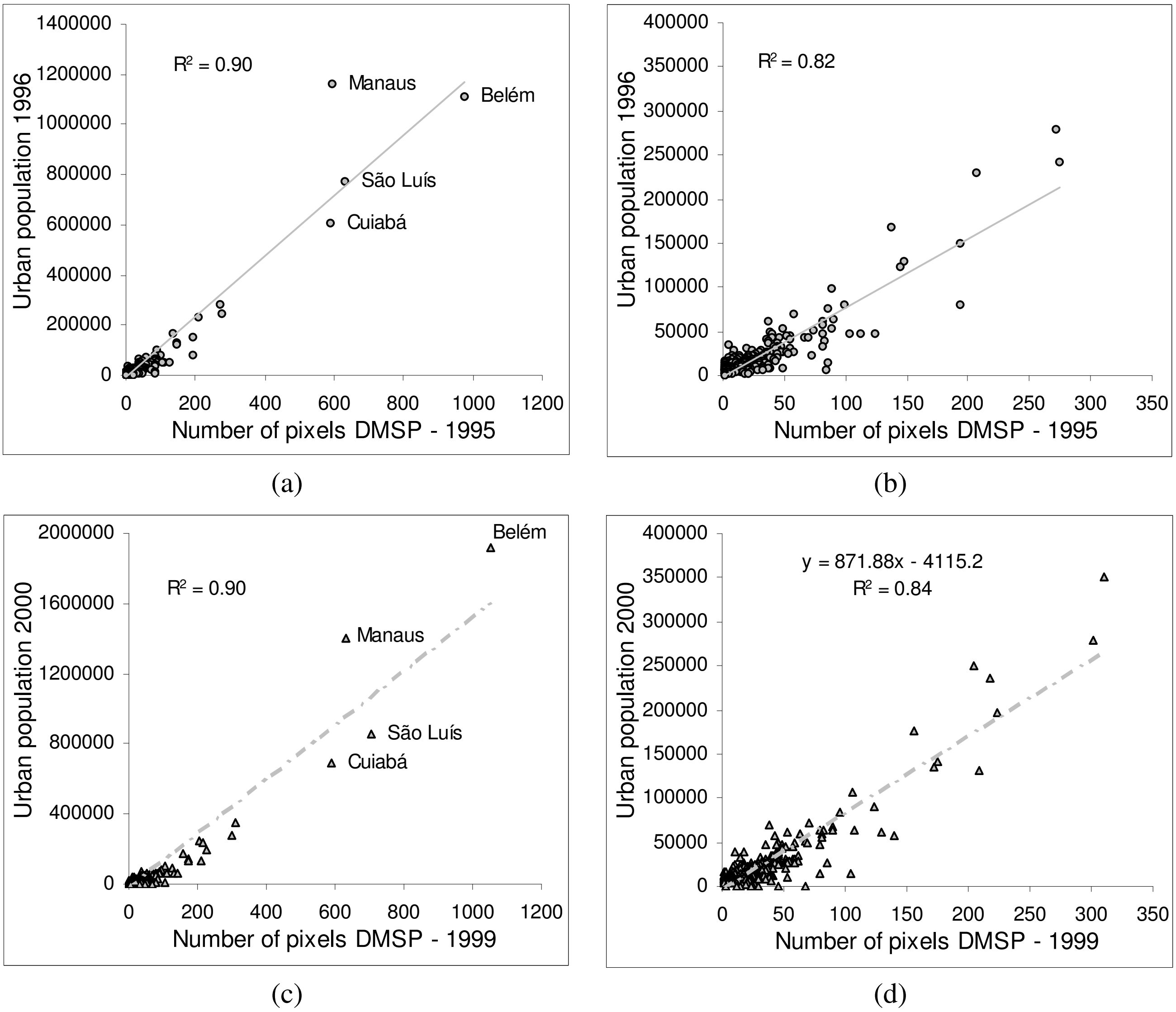
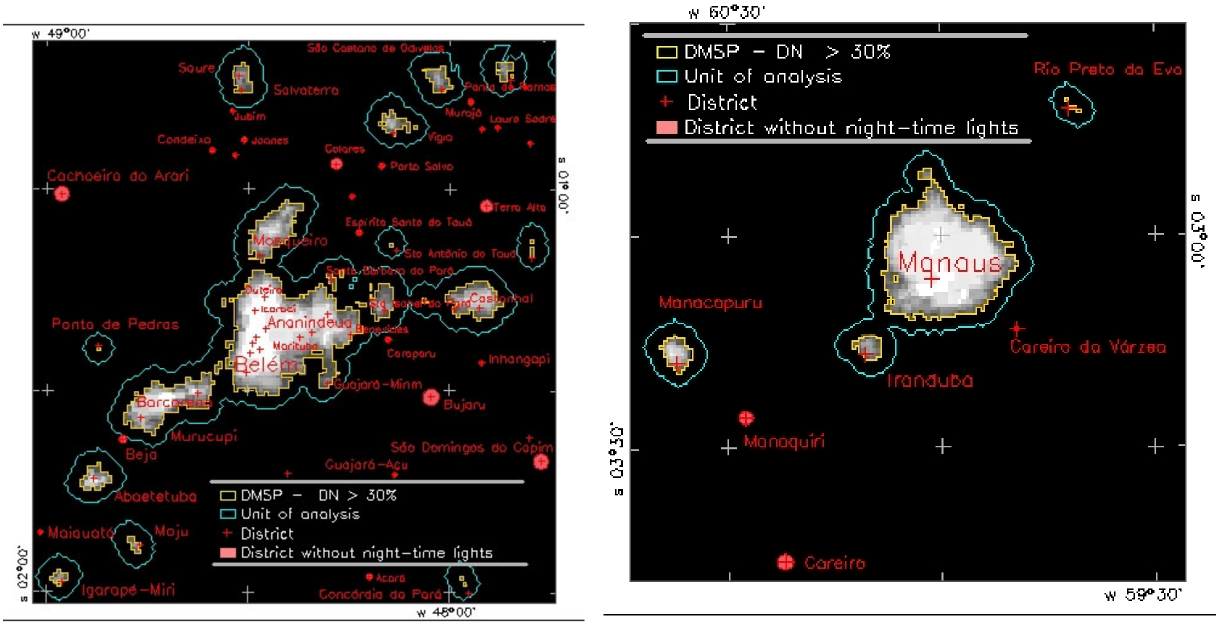


Figure 4. Relations between DMSP-1995 and urban population 1996 (a) and (b); and DMSP-1999 and urban population 2000 (c) e (d). Units of analysis containing the capitals Cuiabá (MT), São Luís (MA), Belém (PA), and Manaus (AM) were excluded at (b) and (d).

In order to better observe the data variability for the units of analysis with urban population less than 400 000 inhabitants, the capitals of the states (Cuiabá (MT), São Luís (MA), Belém (PA), and Manaus (AM)) were excluded at figure 4(b) and 4(d). The capitals are special unit of analysis because they encompass a wide region and consequently, a large number of districts (figure 5). This effect explained the higher urban population values for the unit of analysis containing Belém, which urban population was inferior (1 271 615 inhabitants) than the urban population registered for Manaus (1 394 724 inhabitants) in IBGE 2000 population census. The unit of Belém included several districts as Barcarena, Mosqueiro, Castanhal, and Murucupi, totaling

1 918 073 inhabitants as urban population. On the other hand, the unit containing Manaus just included Iranduba totaling 1 406 708 inhabitants.



(a) (b)

Figure 5. Unit of analysis over Belém (a), and Manaus (b) metropolitan regions in DMSP 2002 night-time light mosaic image.

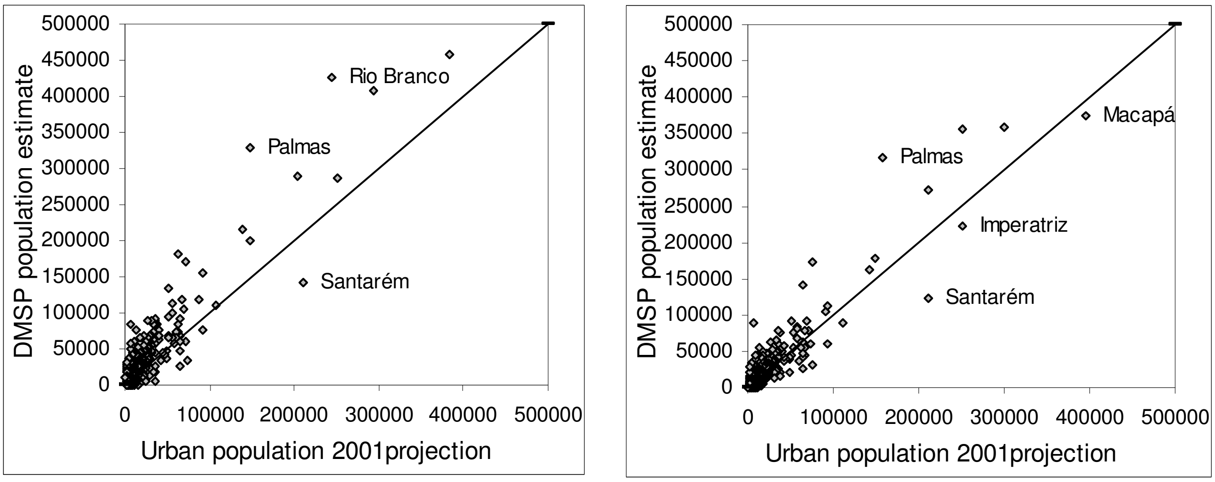
The coefficient of determination values (R^2) obtained for the linear regression analysis indicated linear relation between the night-time lights and the urban population. Even excluding the capitals, when the data dispersion was evidenced, the R^2 values ($R^2 >= 0.82$) were still comparable to those obtained from other authors (Sutton *et al.* 1997, Elvidge *et al.* 2001, Amaral *et al.* 2003). The F values from the variance analyse of the regressions (table 1) confirmed the linear relations. High root-mean-square error (rms) values were obtained due to the urban population range variation in the data: from 77 to 1 918 073 inhabitants.

Table 2. Linear regression variance analysis considering night-time lights pixels DMSP and urban population.

Relation	R^2	**n**	**F**	$F_{value\ P}$	**rms**
DMSP - 1995 x Urban Population 1996	0.90	248	2349.74	7.2E-128	37230
DMSP - 1995 x Urban Population 1996*	0.81	244	1077.61	4.1E-91	14629
DMSP - 1999 x Urban Population 2000	0.90	225	2047.32	2.3E-111	55144
DMSP - 1999 x Urban Population 2000*	0.84	221	1188.18	2E-90	17366

* Excluding the capitals Belém (PA), Manaus (AM), São Luís (MA), and Cuiabá (MT).

From the linear equation that related DMSP-1999 and urban population-2000, the urban population was estimated for 2001 and 2002, considering DMSP-2002 and DMSP-2003, respectively. The scatterplots (figure 6) presents the errors when comparing the DMSP estimates with the urban population values predicted by the official demographic statistics from IBGE population projections.



(a) (b)

Figure 6. Scatterplot comparing urban population estimated from DMSP images and from IBGE urban population statistical projection: (a) DMSP-2002 estimate and IBGE-2001 projection, and (b) DMSP-2003 estimate and IBGE-2002 projection.

The urban population estimated from DMSP-2002 was overestimated compared to the IBGE-2001 population projection. This overestimation is even more frequent for locations where the urban population is inferior to 50 000 inhabitants. The use of a linear equation from DMSP-1999 to estimate urban population can be responsible for the overestimation. The DMSP-1999 mosaic image was generated from only 16 single images, sensitive to cloud cover presence, and with night-time light foci slightly smaller than DMSP-2002 ones. While for DMSP-2002, 516 night-time lights foci were registered, with an average area of 40 km^2, for DMSP-1999, 243 night-time lights foci were identified with an average area of 37 km^2.

The average population difference between DMSP-2002 estimate and IBGE-2001 projection was 11 049 inhabitants, for the 428 analysed locations. These locations have an average of 19 773 inhabitants projected as urban population 2001. Only for Santarém city, the urban population projection was higher than the tendency obtained from the night-time lights foci, even tough the night-time light focus enlarged from 156 to 168 pixels for the 1999 to 2002 period.

The urban population estimates from DMSP-2003 (figure 6.b) presented estimation errors evenly distributed compared to the IBGE-2002 project population. The average difference corresponded to 4 928 inhabitants, for the 385 analysed locations. These locations have an urban population average of 21 831 inhabitants projected for 2002.

Instead of using the urban population statistical projection, a more effective validation for the night-time lights and urban population relations would be obtained with census data for urban population values. Despite the general counting census has a decennial interval, a sampling counting is taking annually (PNAD – the national research by housing sampling), but it is restricted to the principal metropolitan regions and the Amazon region is excluded.

4.3. Field work as reference analysis

During the field campaign (2000, May, 15th to 30th), from Belém to Marabá city in the state of Pará, 551 km, along PA-150 highway were observed. Using a GPS, the geographical coordinates of 49 human settlements were registered. From these total, 42 of them presented public illumination, comprising 7 cities, 26 villages and 9 house settlements. In other two villages and five house settlements the public illumination was absent. Observing at DMSP-2002 mosaic image, only the seven municipal centres (Abaetetuba, Moju, Tailândia, Goianésia do Pará, Jacundá, Nova Ipixuna e Marabá) and one village had its night-time lights registered. Mostly of these cities has the highway as main urban development axis, as presented in figure 6. The village detected at DMSP-2002 is close to Marabá, the south-eastern regional centre on Pará, and corresponds to the PA-150 and Transamazônica crossroad, a highly illuminated place, similar to what was observed at Goianésia do Pará (figure 7).

Figure 7. DMSP-2002 mosaic image and the field trajectory. Red points correspond to populated places along PA-150 highway. Detail of the public illumination at the city of Goianésia do Pará.

Analysing the initial and final presence of public illumination on the urban area of the cities, registered by GPS coordinates (figure 6), evidenced the correct position of nigh-time light foci, as observed at DMSP-2002. This result emphasizes the correspondence of DMSP night-time lights as indicators of urban extension.

Travelling along the Marabá rural area, a village called Brejo do Meio was visited. It is a settlement of about 2 000 inhabitants, occupying an area of about 2.5 km^2, with some basic urban equipment as streets, public squares, schools, churches and external public illumination. However, there was any evidence of night-time lights for Brejo do Meio at DMSP-2002. This result suggests that night-time lights are registered at DMSP mosaic image for areas with extension superior to the observed at this village.

5. Conclusions

This paper analysed the potential of DMSP night-time lights mosaic images to identify the presence and to estimate urban population in the Brazilian Amazonia region. To achieve this goal, DMSP mosaic images for 2002 and 2003 had been generated, considering a six-month time interval, and minimizing the presence of ephemeral lights - forest fires in the Amazonia region. This procedure was essential to the proper identification of night-time lights emitted from human settlements.

The unit of analysis, defined based on buffer zones from DMSP-2002 night-time lights foci, enabled the comparison between frequency of night-time lights pixel and urban population values. All urban settlements with population superior to 10 000 inhabitants can be precisely detected by DMSP night-time lights. Most of the settlements (85%) with population between 5 000 and 10 000 inhabitants can be identified with night-time lights. And some small settlements, with urban population inferior to 5 000 inhabitants, can have its night-time lights detected by DMSP image data.

The results from the linear regression, with determination coefficients superior to 0.8, indicated the potential utility of night-time lights to estimate urban population in the Amazonia region. The simplicity of the linear model, and the errors between urban population estimated by DMSP data and IBGE projection values (an average of 4 928 inhabitants), indicate the use of DMSP image data to monitor/follow the urban population evolution in settlements with more than 20 000 urban inhabitants. For this purpose, some additional calibration with actual census data would confer more confidence the linear model.

The fieldwork data evidenced the DMSP night-time lights restrictions to detect small settlements with some urban structure: DMSP image data can only register settlements with more than 2.5 km^2 of well-lighted areas. However, the fieldwork attested the precise location, the initial and final extension of the night-time lights foci. These information, in addition to the fact DMSP night-time lights can be a reference of the urbanized areas (Amaral et al., 2003), indicate the use of night-time lights as an ancillary data to study the spatial distribution of the urban population in the Amazonia region.

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