Assessment of image restoration techniques to enhance the applicability of MODIS images on Amazon floodplain landscape studies

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Abstract. The Amazon floodplain represents a significant portion of the world's wetlands, and participates actively in the carbon cycling in the region. Due to its large extent, remote sensing is the most appropriate tool for studying the Amazonian landscape; image acquisition, however, is highly hindered by the frequent cloud cover. Medium resolution sensors such as MODIS can overcome this problem with a larger swath and high frequency of image acquisition, at the expense of spatial resolution. In the present study, MODIS images were submitted to an image restoration algorithm (RESTAU), to assess the capability of this technique for recovering the spatial detail lost due to the sensor PSF characteristics. Landsat TM and MODIS Aqua reflectance images were acquired for a region of the central Amazon during the high water season. These images were co-registered and the MODIS imagery was submitted to the restoration algorithm. Two sets of TM and MODIS images were then analyzed visually and by the calculation of landscapes indices (*i.e.* area, shape and patch aggregation). The results show that image restoration can improve the spatial information content of MODIS imagery as whole, but gains are more effective towards area estimations, whereas mapping of shape is still highly affected by scale even after application of the algorithm. Overall, it is suggested that use of image restoration could increase the applicability of MODIS as a tool for area estimations and continuous monitoring of floodplain cover, while accurate delineation of shape still requires higher resolution data to yield acceptable accuracies.

Palavras-chave: MODIS, remote sensing, Amazon floodplain, image restoration, spatial resolution, sensoriamento remoto, planície de inundação Amazônica, restauração de imagens, resolução espacial.

1. Introduction

The Amazon basin wetlands comprise more than 1 million square kilometers in area, with the river floodplain alone exceeding 300 thousand square kilometers (Junk, 1997). Due to its size, it contributes significantly to the global carbon cycle, representing an important source and sink of many forms of C (Crill et al, 1988) and especially a potential source of methane to the atmosphere (Melack et al, 2004).

Landscape zonation in the floodplain results mainly from the variation in river stage and ensuing flooding of adjacent areas. This process and the variations in floodplain topography and pedology result in remarkable heterogeneity of the land cover both in terms of space and time. This variability and the impressive dimensions mentioned above make remote sensing data the most adequate way to thoroughly assess Amazonian floodplain dynamics.

A major constraint observed for these applications, however, is the near constant cloud cover, which prevents a wider use of optical imagery. Such problem may be circumvented by either the use of sensors with a high temporal frequency of acquisition, or by the use of Radar imagery. The latter, however, although effective for vegetation and geological studies, lacks the ability to convey information about water bodies, which represent a significant parcel of the floodplain landscape.

The MODIS sensor, aboard the Terra and Aqua NASA platforms, has attractive features for the study of the Amazon wetlands. It provides optical information at the visible to short wave infrared wavelengths in seven spectral bands, exhibits good radiometric resolution, provides synoptic coverage of sizeable areas and is available free of charge in a variety of derived products. In addition, most of these products are already calibrated for geometrical, radiometric and atmospheric errors. Moreover, as the sensor is replicated in two different platforms, it has the ability to provide acquisitions as much as twice a day for most regions in the globe, increasing the probability of cloud free images for a given study site.

The main restriction imposed on MODIS potential uses is that the improvement in acquisition rate is allowed by a reduction in the spatial resolution, making it less useful for studies on finer scales. A key aspect to be assessed thus is how much this tradeoff affects the suitability of MODIS data use for Amazon floodplain studies, and how processing techniques that improve spatial resolution may contribute to a better assessment of surface features and processes.

Having this in mind, the present article evaluates the effectiveness of an image restoration algorithm into improving the spatial resolution of MODIS imagery, and the associated gains for the study of the Amazon floodplain.

2. MODIS Image Restoration

The image restoration problem attempts to recover an image that has been degraded by the limited resolution of the sensor, as well as by the presence of noise using a priori knowledge of the degradation. The spatial resolution of images obtained from satellite sensors is degraded by sources such as: optical diffraction, detector size, electronic filtering and satellite movement. As a consequence, the effective resolution is, in general, worse than the nominal resolution that corresponds to the detector projection on the ground and does not take into consideration the sensor imperfections.

The degradation of spatial resolution can be approximated by a gaussian blur model (Fonseca e Mascarenhas, 1987). This model is similar to a low-pass filter, which produces an image with blurred appearance. A restoration filter, a high-pass filter that is applied to the image to reduce its blurred appearance, can compensate the blurring effect. Restoration filters based on the Modified Inverse Filter (MIF) technique have been implemented to process different satellite images (Fonseca et al., 1993, Boggione, 2003). The filter can be combined to the interpolation process to generate images with a better resolution over a finer grid (Fonseca et al., 1993). The restoration algorithm used in the present work is based on MIF and was implemented using common C++ and Trolltech Qt library (RESTAU).

To design the MIF it is necessary to know the EIFOV (Effective Instantaneous Field of View) sensor parameter, which is as a function of the frequency in which the MTF (Modulation Transfer Function) is equal to 50% of its maximum value. This parameter can be estimated using images of ground or simulated targets (Bensebaa et al., 2004). For MODIS images, the MTF values indicated by Barnes et al. (1998) have been used to calculate the EIFOV values for each band. **Table 1** presents the EIFOV values in the across- and along-track directions for MODIS bands 1-7. These values were used to design the restoration filters applied to MODIS imagery in the present study.

Table 1 – Calculated EIFOV values for MODIS band 1 and 2 (250 m)

Band	Nominal Resolution	Across-track EIFOV	Along-track EIFOV
1	250 m	299.6 m	261.5 m
2	250 m	291.1 m	253.9 m
3	500 m	560.0 m	499.1 m
4	500 m	546.1 m	499.3 m
5	500 m	540.0 m	520.0 m
6	500 m	540.0 m	520.0 m
7	500 m	537.8 m	521.3 m

3. Study Site

The selected study area corresponds to the Curuai Lake floodplain, situated along the Amazon River, at 900km from the river mouth, near the confluence of the Amazon and Tapajós rivers (1.3^{o}S and 55.43^{o}W), and the cities of Óbidos and Santarém (Pará state, Brazil). This area may be regarded as representative of the environmental conditions found at the central portion of the Amazon floodplain.

The Curuai floodplain comprises around 20 interconnected lakes, which collapse into bigger water bodies during the high water season, covering about 3,500 km^2 (Barbosa, 2005). The annual water level variation is around 5 meters. Water starts to rise from December to May, reaching a peak around June and July, and then receding to its minimum in November.

The main landscape cover types observed in the region are: forested areas, which may become flooded or even totally submerged during the high water season; herbaceous vegetation, mainly composed by grasses (pasture and macrophytes) and areas of exposed soil, which are progressively recolonized by terrestrial species during the low water season.

4. Methods

Landsat TM images (path/row 228/61) and MODIS Aqua MYD-09 (daily surface reflectance) products were obtained for the period of maximum water level, corresponding to the date of May 2, 2004. Also, a corresponding orthorectified ETM+ scene was obtained from the Global Land Cover Facility database (http://glfc.umiacs.umd.edu), to be used as reference for geometric correction.

Geometric correction of TM images was performed with the use of Ground Control Points and the orthorectified ETM+ image as a reference. The overall RMS error was less than 1 pixel. The final reference system was UTM/WGS 84. After the geometric correction, both scenes were clipped between 1.83_{o}S and 2.73_{o}S and 55.03_{o}W and 55.97_{o}W.

As MODIS images are provided already corrected for atmospheric and geometrical effects, only a reprojection to the UTM coordinate system and subsetting were performed. A conversion from 16 to 8 bit values was also executed, using a dynamic range optimization to minimize information loss due to bit compression (Arai et al., 2000). This conversion was necessary due to software constraints in posterior processing steps.

MODIS image restoration was performed by the use of the RESTAU algorithm described in Section 2, generating 125m and 250m bands from the original 250m and 500m bands, respectively.

Two sets of bands were selected for analysis: one in the Near Infrared (NIR), consisting of TM band 4 and both original and restored MODIS band 2 images, and one in the Shortwave Infrared (SWIR), comprising TM band 5 and both MODIS band 5 images. The two sets allowed analysis of restoration effects on both 250m and 500m original resolutions.

The image sets were then subjected to a simple thresholding, generating binary water/non-water images. Thresholds were selected by analyzing the spectral response of water bodies in the scene, and then selecting the appropriate digital number that best separated open water areas from other cover classes. The study area was divided into 48 square samples of equal size, to allow statistical analysis. A series of landscape metrics were calculated for all sample images using the software FRAGSTATS (McGarigal & Marks, 1995), in order to evaluate the effect of MODIS restoration into measurements of area, shape and distribution of surface features. All calculations were performed regarding the open water cover class.

For area description, Total Cover Area (TA) and Percentage of Land Cover (PLAND) were calculated, as well as the Largest Patch Index (LPI), which expresses the size of the largest patch as a percentage of the total square area. For shape characterization, Perimeter (P) Perimeter/Area Ratio (PARA) and Shape Index (SHP) were determined, the latter consisting of the patch perimeter divided by the calculated perimeter for the most compact representabale shape with the same area (*i.e.* a square). For spatial distribution (*i.e.* configuration), both the Number of Patches (NP), and the Aggregation Index (AI) were computed, where AI equals the number of observed adjacencies between class pixels as a percentage of the maximum possible number adjacencies (*i.e.* a single compact patch).

To compare differences in the performance of each image in the set, each of the computed metrics was submitted to a paired *t* test. The same test was also applied for comparing samples derived from the same image type in each set, in order to assess the influence of variations in spectral response (NIR and SWIR) and selected threshold levels on the obtained results.

4. Results and Discussion

An initial visual inspection of the restored MODIS images revealed a noticeable gain in detail, especially in terms of feature discrimination, when compared with both the original datasets and TM scenes, for both 250 and 500m images (**Figure 1**).

It was noted, however, that the restoration process introduced some artifacts in the image, in the form of duplicated borders on regions of high contrast, such as river margins in the infrared bands. A simple statistical analysis revealed the preservation of the mean DN value, with less than 1% difference, and increase of 7% to 20% in variance. This behavior agrees with the expectations for a good restoration filter, which increases the informational content without significantly altering the original radiometry of the scene (Boggione, 2003).
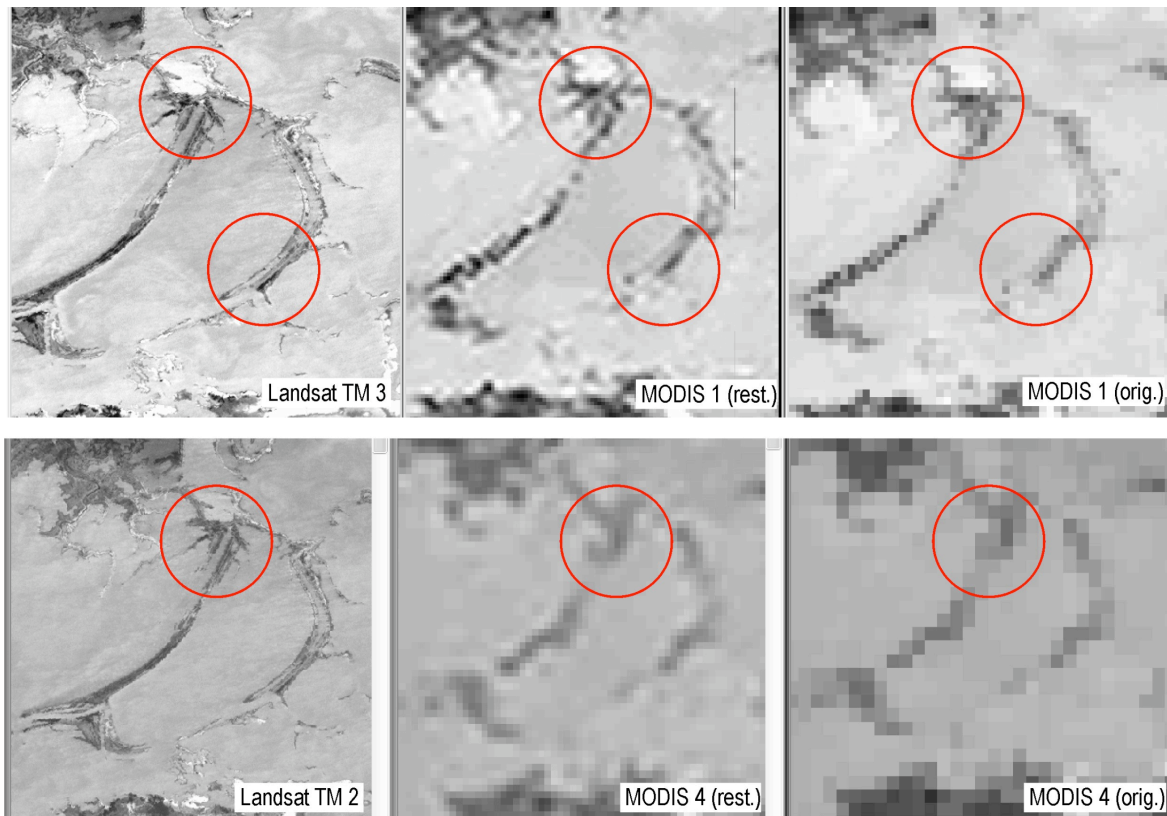
Figure 1 - Effect of the image restoration algorithm on MODIS bands. Highlighted areas indicate gain in spatial detail and better reproduction of shape. Orig. = original MODIS images; Rest. = restored MODIS images.

For the measurements of Total Area (TA), it was observed that estimations obtained from all three NIR image sources were similar until around 5000ha, from where MODIS derived areas consistently underestimated the TM measurements (**Figure 2**). In addition, it is worth noticing that from between 1000 and 2000 ha, the reverse trend was observed. Both restored and original MODIS images yielded area measurements significantly different from the TM data ($p < 0.01$), and also different from each other ($p = 0.016$). For the SWIR imagery, the restoration algorithm was able to produce measurements much closer to the TM results in the 0 to 1000ha range, and then displaying a trend to underestimate values similar to that observed for the NIR data. Original MODIS SWIR underestimated areas throughout the whole range of measurements. In fact, only TM and MODIS Original results were significantly different ($p < 0.001$).

It's interesting to notice, however, that despite the observed trends in area estimations, the Percentage of Class Cover (PLAND) differed significantly only between MODIS original and restored NIR estimations and between TM and MODIS Original SWIR data ($p = 0.02$), meaning that the relative nature of the PLAND measure somewhat masked the effect of spatial resolution on the derived measurements. This way, although MODIS area estimates are expected to be underestimated for the Amazon floodplain, relative representative of cover classes can still be estimated with reasonable accuracy.
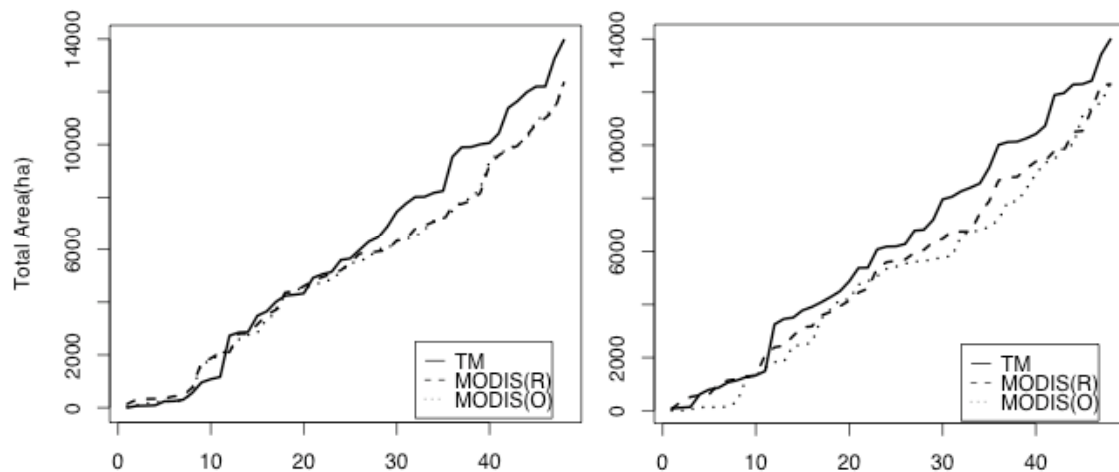
Figure 2 – Calculated Total Areas, ranked by size, for NIR (left) and SWIR (right) sets. MODIS(R) = Restored; MODIS (O) = Original.

The metric Number of Patches (NP) reveals the full effect of pixel size on classification results, with TM NP values about three orders of magnitude larger than the MODIS estimates. This result may explain in part the reason why the difference in area measurements increases progressively for MODIS and TM imagery. As the dominance of a given class increases in the scene, underestimation due to lack of capacity in capturing fine detail increases proportionally.

For the Largest Patch Index (LPI) metric, no significant differences were noticed except between TM and MODIS Original in the NIR set. This result is understandable, as gains obtained from higher resolution imagery are mostly concentrated on the detection of smaller areas in the landscape, and thus not likely to affect LPI measurements as much as other metrics.

Measurements of Perimeter (P) and shape (SHP and PARA) were the ones most affected by image spatial resolution. In all cases, the differences between TM and MODIS measurements were strongly significant ($p < 0.0001$), and even restored and original images exhibited significant differences ($p < 0.001$ for NIR, $p = 0.04$ for SWIR).

The last evaluated metric, the Aggregation Index (AI), was the measurement most improved by image restoration, especially in the SWIR image set, as can be seen in **Figure 3**. Differences between restored MODIS and TM were not significant in the NIR range, and, although significant in the SWIR, differences were greatly reduced when compared to the original MODIS imagery ($p = 0.003$ vs. $p = 1.32 \times 10^{-6}$).

The comparison between metrics derived from the equivalent images of each sensor (e.g. TM NIR x TM SWIR), at the different spectral regions yielded no significant differences between any measurements for the TM imagery ($p > 0.05$ for all cases). These results confirm the similarity between water mappings obtained at the different wavelengths. For both original and restored MODIS image sets, significant differences were observed only for NP, AI, SHP, and PARA. Such variation can be explained by the aforementioned sensitivity of these measures to resolution changes, whereas the similarity between more robust metrics still indicate that NIR and SWIR classifications were analogous between equivalent MODIS images.
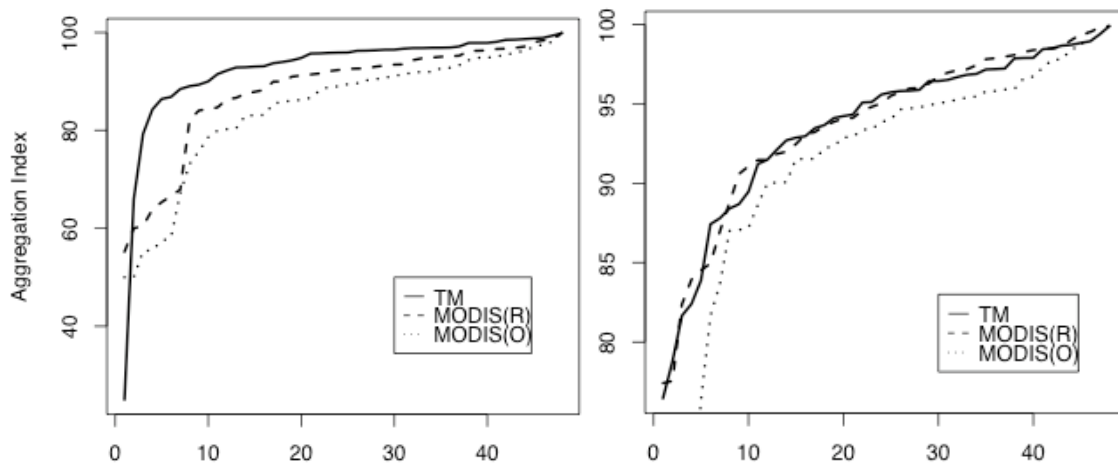
Figure 3 – Calculated Aggregation Index, ranked by size, for NIR (left) and SWIR (right) sets. MODIS(R)=Restored; MODIS (O)=Original.

5. Conclusions

Overall, the application of image restoration to MODIS imagery was capable of recovering some spatial information and improving the information content of MODIS imagery. Although the variations arising from such differing spatial resolutions were still present after restoration, the algorithm was capable of reducing the gaps between results obtained from TM and MODIS imagery in most cases, with considerable enough gains to generate sets of measurements significantly different than those computed from original MODIS imagery. As expected, measurements of shape such as perimeter and shape indexes were the ones most sensitive to scale and spatial resolution changes, thus exhibiting the smallest improvements.

These results indicate that the use of MODIS imagery can be regarded as an alternative to higher resolution sensors for applications that demand only cover area estimations, such as modeling of carbon emission, estimations of loss in vegetation cover or variation in water optical parameters. These applications can also benefit from the improved frequency of acquisition for continuous monitoring purposes. For accurate mapping and delineation of surface features, however, MODIS data is expected to be of less applicability, unless used for mapping of large and homogenous areas, which are seldom observed in the Amazon floodplain.

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