Global Burned Land Estimation in Latin America using MODIS Composite Data

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ABSTRACT

This paper presents results of the AQL2004 project, which has been developed within the GOFC-GOLD Latinamerican network of remote sensing and forest fires (RedLatif). The project intended to obtain a monthly burned land mapping of the whole continent, from Mexico to Patagonia, using

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MODIS reflectance data. The project has been organized in 3 different phases: Acquisition and pre-processing of satellite data; the discrimination of burned pixels, and the validation of results. In the first phase, the input data were the 32-day composites of MODIS 500 m reflectance data generated by the GLFC of University of Maryland. The discrimination of burned areas was addressed in two phases: seeding of burned core pixels using post-fire spectral indices and multitemporal comparison, and mapping of burned scars using contextual techniques. The validation phase was based on visual analysis of Landsat and CBERS. Validation of the burned land category showed an accuracy ranging from 30 to 60%, depending on ecosystems and vegetation species. The total burned area for the whole year was estimated in 153 215 sq km. The most affected countries in relation to their territory were Cuba, Colombia, Bolivia and Venezuela. Burned areas were found in most land covers; however herbaceous vegetation (savannas and grasslands) presented the highest proportions of burned area, while perennial forest the lowest. The importance of croplands in the total burned area should be taken with reserve, since this cover presented the highest commission errors. The importance of generating systematic products of burned land areas for different ecological processes is emphasised.

Keywords: Burned Area, Remote Sensing, Latin America, MODIS

INTRODUCTION

Forest fires have an important role in global ecological and climate systems, being responsabile for a significant part of greenhouse gas emissions (van der Werf *et al.*, 2004) to the atmosphere and for land degradation and soil erosion processes (Levine, 1996). Additionally, many studies have identified wildland fires as the most extended tool for forest clearing in the Tropical regions (Roberts, 2000), and therefore the importance of studying global patterns of fire occurrence becomes increasingly relevant. According to Liousse et al. (2004) the amount of CO2 emissions derived from biomass burning in Latin America is 8 times larger than emissions derived from fossil fuel combustion. Therefore, it is critical to improve current estimations of burned land areas in the continent, from an ecological and management point of view.

The availability of wildland fire statistics is mostly reduced to developed countries, while in other countries the estimations are generally poor or not available. According to the latest FAO statistics (FAO, 2006) from 1998 to 2002 more than 3 million hectares were burned in Latin America. These

estimations are very low compared to other projects based on satellite data for the same region (Boschetti *et al.*, 2004), and should be related to the lack of absence of consistent assessment of burned areas in most developing countries.

The use of remotely sensed data is a sound alternative to traditional field methods for estimating burn land areas. Earth Observation data provides timely, cost effective and spatially comprehensive view of fire affected areas and fire occurrence patterns (Di Bella *et al.*, 2006). The use of these data for fire effects assessment has grown notably in the last decades, using both high and low resolution satellite sensors (Ahern *et al.*, 2001). Global approaches to map burn areas were based in NOAA-AVHRR images during the 90's, being very common the multitemporal comparison between spectral vegetation indices (Barbosa *et al.*, 1999; Kasischke & French, 1995; Martín & Chuvieco, 1995; Pereira, 1999), although some combination of thermal and optical channels were also used (Fraser *et al.*, 2000).

More recently, other sensors with greater sensitivity to discriminate burn scars have been used to create a global inventory of burned areas. In 2000 two world wide projects were developed: the GBA2000 (Tansey *et al.*, 2004) and the Globscar (Simon *et al.*, 2004). The former was based on SPOT-Vegetation data and it was coordinated by the Joint Research Center of the European Union. The latter was an initiative of the European Space Agency, and it was based on ERS-2 ATSR images. Finally, the MODIS program soon plans to release a standard product on burned land areas at global scale, which will be based on a multitemporal change detection approach to analyze differences between modeled and actual reflectance, and to take into account BRDF corrections (Roy *et al.*, 2005b). Other authors have use active fire detections derived from thermal channels to obtain global estimates of burned areas (Giglio *et al.*, 2006)

The bottleneck of these global approaches is the assessment of results, which is very complex and costly. However, properly assessment of global products is becoming increasingly important in order to reduce uncertainties when using them as an input to other estimation models (Boschetti *et al.*, 2004). The critical need to assess global products has led to the creation of regional networks, which can take advantage of local expertise to tune up global algorithms and make them more suitable for specific ecosystems. The Global Observation of Forest and Land Cover Dynamics (GOFC-GOLD: http://www.fao.org/gtos/gofc-gold/index.html) program is a coordinated international effort working to provide ongoing space-based and in-situ observations of forests and other vegetation cover for the

sustainable management of terrestrial resources and to obtain an accurate, reliable, quantitative understanding of the terrestrial carbon budget. Within this program, the Fire Implementation Team has encouraged the creation of regional networks, which provide a mechanism for sharing of resources and expertise. Within this framework, a Latin American GOFC-GOLD network (named RedLatif) was created in 2002, which intended to foster the relationships between scientists working in remote sensing and fire applications throughout the continent. One of the first objectives of this network was the creation of a burn land map of the region, which could be used to assess the spatial and temporal patterns of fire occurrence at the continental scale.

The importance of Latin America in the context of fire ocurrence and global deforestation is evident. A recent report from the FAO (2006), focused on the evolution of forested areas between 2000 and 2005, emphasizes the importance of Latin America in global deforestation rates. In fact, this region has the highest rate of annual forest conversion, with almost 5 million ha year-1, which accounts for 67% of the world's deforestation. A great amount of this deforestation is caused by wildland fires (Cochrane *et al.*, 1999), and therefore it is critical to better understand fire occurrence patterns in the continent. Additionally, Latin American biomass burning is a very important source of global gas emissions, around 16% according to recent studies (van der Werf *et al.*, 2006)

The main goal of this paper is to generate a continental map of burned areas and to analyze the spatial and temporal patterns of fire occurrence derived from this product. This project, developed within the Redlatif network, was named AQL2004 (*Area Quemada en Latinoamerica*, the Spanish version of Burned Land Areas in Latinamerica for 2004). The project was intended to improve current estimations of burned areas in the continent, as an input to global analysis of ecological impacts of fires in the continent, to better understand the relations between fire occurrence and biodiversity, and to improve atmospheric emissions derived from wildland fires. The extension of the area should facilitate to obtain a global perspective of spatial and temporal patterns of fire occurrence that may be applicable to other continents

The AQL2004 project was proposed on a volunteer basis as part of the RedLatif network activity, and without specific funding. Therefore, input data for generation and validation of the product was restricted to satellite data that may be publicly available. As we will comment later, this limitation has impacted the results of the project, but it has also provided a good cooperation scenario that might be

useful for other active networks. External funds were limited to coordination activities (three meetings) and were obtained from the NASA-START program.

METHODS

Image acquisition and preprocessing

Moderate Resolution Imaging Spectroradiometer (MODIS: http://modis.gsfc.nasa.gov/about/) images were selected for the project, since they provided a good spatial, spectral and temporal resolution while being freely downloadable. The MODIS program offers a wide range of standard products covering land, atmospheric and water applications (http://modis.gsfc.nasa.gov/data/dataprod/index.php). The standard reflectance product MOD09 is an 8 day composite of atmospherically corrected and calibrated reflectances at 500x500 m pixel size, covering the whole Earth in tiles of 1200x1200 km using a Sinusoidal Projection system. Additionally, the MODIS program offers another reflectance product (MOD43) that includes a correction of the observation and illumination effects (commonly referred to as Bidirectional Reflectance Distribution Function, BRDF).This product includes the same bands as the MOD09, but with lower spatial (1000x1000 m) and temporal (16 days) resolution. Finally, the University of Maryland's Global Land Cover Facility (GLCF) compiled 32 day composites of the MOD09 product. This is not a standard product of the MODIS program, but it has been used for land cover analysis and is also freely available (Townshend *et al.*, 2003). The product has the same spatial and spectral resolution as MOD09, and chooses for each pixel the second lowest albedo value among the four 8-day composites that formed a single 32-day product (http://glcf.umiacs.umd.edu/data/modis/500m32day.shtml). This criterion is used to reduce clouds and cloud shadows in the final composites. The product includes the 7 reflectance bands of MODIS with 500x500 m pixel size (table 1). This product is mosaicked by continents and uses the Goode Interrupted Homolosine projection. After analysing the advantages and disadvantages of the different products, the 32-day composites produced by GLCF were selected, since they provided an adequate temporal resolution for our project (monthly burn area estimations) and reduced the effects of cloud and cloud shadow contamination of the 8-day composites. In addition, the geometric pre-processing of the data over the continent was easier that for the standard MODIS products that are offered in 1200x1200 km tiles.

Twelve 32-day composites were downloaded from the GLCF site, covering the period from December 2003 to December 2004. The complete mosaic of North and South America was divided in 12 regions, which were assigned to each participant groups. Each group was aimed to develop a basic discrimination algorithm for the study area that could be later compared with other ecosystems for deriving a global burned land algorithm.

In spite of the long series of daily data, cloud contamination was still observed in the 32-day composites, especially in some tropical regions of the Amazon Basin and Central Venezuela. A cloud screening was performed with three reflectance bands, using the following criteria:

If (band 2 > 2.5 AND band 3 > 6 AND band 5 / band 3 > 0.7) then Cloud

To avoid confusions between burn scars and low-reflectance over some non-vegetated areas, such as dark soils or water, a fuel mask was derived from the Vegetation Continuous Fields (VCF) dataset (Hansen *et al.*, 2002). The product was downloaded from the GLFC web site (http://glcf.umiacs.umd.edu/data/modis/vcf/) and included three data files, with percentage of trees, bare soil, and herbaceous vegetation. The values are scaled between 1 and 100 and the sum of the three layers estimates 100% of ground cover. The VCF version used in this project was produced by the GLCF at the University of Maryland from the 32-day MODIS Composite data for the period between November 2000 and 2001, and it was generated from spectral unmixing analysis.

For the AQL2004 project, the non-fuel category was defined as pixels that had more than 80% of bare soil, or alternatively those that met two conditions: less than 70% herbaceous and less than 10% trees. Otherwise, they were considered areas that could be burned.

Considering the great variety of ecosystems in Latin America, this criterion was not applied at the beginning of the process to avoid potential errors in areas of low vegetation coverage. It was used as a filter at the final stages, but regional thresholds were also applied in the semi-arid regions of Argentina and Chile.

Burned land discrimination methods

Burn scar mapping was based on a two step approach. The first step was dedicated to selecting the most clearly burned pixels in each burn scar. The second step was aimed at improving the mapping of each burned area by including the neighboring pixels of those previously identified. The goal of the first phase was to reduce, as much as possible, the commission errors (pixels labeled as burned areas

that were not actually burned), while the objective of the second phase was to reduce the omission error (pixels that were indeed burned and were not classified as such). This two-phase burned land mapping approach should produce better results than trying to classify all the burn scars in a single algorithm, since it was expected to find a great diversity of spectral signatures in such a large territory.

Discrimination of "core" burned pixels

The first phase of our discrimination algorithm was based on multiple thresholds on post-fire images as well as on multitemporal change detection. From the original 32-day reflectance products, two vegetation indices were computed to improve the separability of burned and unburned areas. The Normalized Burn Ratio (NBR) was proposed in the 90's to discriminate burned areas (Key & Benson, 2002; López García & Caselles, 1991), based on the contrast between near infrared (NIR) and short wave infrared (SWIR) reflectance.

$$NBR = \frac{\rho_{SWIR} - \rho_{NIR}}{\rho_{NIR} + \rho_{SWIR}} \quad (1)$$

where ρ_{SWIR} and ρ_{NIR} are NIR (generally from 700 to 900 nm) and SWIR (from 2100 to 2300 nm) respectively. The index has a range from -1 to 1, with the larger number being the severest burn. This index has been extensively used lately in the framework of the Firemon project (Key & Benson, 2004), and will be used operationally in the US for mapping burn severity from Landsat-TM/ETM+ data (http://burnseverity.cr.usgs.gov/fire_main.asp). For this paper, the index has been defined after changing the sign (ρ_{SWIR} -ρ_{NIR} instead of ρ_{NIR}-ρ_{SWIR}) to keep the scale consistent with the index definition, since reflectance in the SWIR is higher than in the NIR for most recently burned areas. Since this index is intended to discriminate burn severity, only high values of the index should be of interest for the first phase of the project, leaving the intermediate values to be classified in the second phase.

In addition to the NBR, a Burned Area Index (BAI) was also used in this project to assure that the pixels selected in the first phase were as close as possible to charcoal signal, thus avoiding false alarms with other potential mixtures of dark reflectance objects. The BAI was developed initially for NOAA-AVHRR images (Martín, 1998), and was recently adapted to MODIS data using also the NIR and SWIR bands (Martín *et al.*, 2005). This index is defined as the inverse quadratic distance of every pixel to the convergence point of charcoal:

$$BAI = \frac{1}{(Pc_{SWIR} - \rho_{SWIR})^2 + (Pc_{NIR} - \rho_{NIR})^2} \quad (2)$$

where ρ_{SWIR} and ρ_{NIR} have the same meaning as in (1), and pc_{SWIR} and pc_{NIR} are the convergence points in the same bands. After an analysis of sampled burned pixels in different types of fires, they were fixed as 0.2 and 0.08, respectively.

The thresholds for discriminating burned pixels were based on NBR and BAI values of the post-fire image, as well as the multitemporal comparisons of these indices with previous images. These images were computed by post-fire (t) minus pre-fire (t-1) values. The pre-fire conditions were taken from the 32-day composite previous to the one that was being analyzed, starting in January 2004, which was the first target composite and was compared to December 2003, and ending in December 2004.

The specific threshold values were obtained from a sample of 485 MODIS pixels extracted from burn scars in Argentina, Colombia and Brazil and covering different months of the year. As said previously, the main goal of the first phase was to keep commission errors to a minimum, and therefore the selection of thresholds was based on a low percentile of the total pixels classified as burned areas in the sampling sites. The percentile was changed iteratively to test which value provided consistent classification in all study sites and land-cover types being analyzed. The final values are included in table 2. With these values, 12% of the sampled pixels were detected as burn areas. This implies a great omission error, but our main goal in this phase was to avoid confusion with other covers.

The final step of the first phase was to eliminate small clusters of pixels. Since the minimum target burn scar was 250 ha, small groups of pixels were not very reasonable and would have created severe noise. Therefore all patches with less than 5 pixels (125 ha) were eliminated. It was expected that the final patches would be greater than this size after the contextual algorithm was applied.

Contextual algorithm

The second step in our processing method was intended to refine the discrimination of burn scars within those areas previously identified as being burned. In order to do this, a contextual algorithm was developed to take into account the similarity of neighboring pixels to those previously labeled as

burned areas. In this case, the goal was to reduce omission errors by including those pixels that might be less severely burned or those with a weaker charcoal signal.

The criteria to extend the core pixels to their surroundings were based on the geographical and spectral similarity of targeted pixels with those already identified as burned areas. As a criterion of geographical similarity, a maximum distance for inclusion was established, while the spectral criterion to add a pixel to the burned area was based on comparing the BAI values of that pixel with those of the local environment. The comparison of pixel values with the local environmentt has been previously used in burned land mapping (Fernández *et al.*, 1997), and it is routinely used in fire detection algorithms (Martín *et al.*, 1999). For this project, the BAI was used as a measure of charcoal similarity, and the criterion to include a pixel was based on whether that pixel had a BAI value above the average of the local environment, as defined by a certain window size centered in that pixel.

In summary, a pixel would be added to a burn scar when its distance to any pixel in the burn scar was below a certain threshold and when its BAI value was above the average BAI of the local envirnoment. Several maximum distances to the core pixels were analyzed (from 3 to 11 km) studying their performance against sampled burned areas from which burn perimeters were available. A similar approach was applied to find out the most convenient window size to extract average BAI value for estimating the local environment. Window sizes from 3x3 pixels to 21x21 pixels were tested (figure 1).

Analysis

Geographical patterns of the results were based on latitude and longitude fringes on one hand, and land cover areas on the other. The former was aimed to provide a zoning analysis of fire occurrence, while the latter was intended to offer a global view of the most affected ecosystems. The land cover layer was extracted from the MOD12Q1 (v.4) standard MODIS product, generated by the University of Boston (http://www-modis.bu.edu/landcover/userguidelc/intro.html). This product was made from MODIS data from the period 1/1/2001 to 12/31/2001, and it is based on reflectance data, spectral vegetation indices and surface texture information. The product is offered for different land cover classification systems. We selected the classification system defined by the International Geosphere Biosphere Program (IGBP) land cover project (Belward, 1996), which includes 17 global land cover categories. The product was available in Interrupted Goode Homolosine projection, thus facilitating the comparison with the AQL2004 results. The world mosaic was downloaded from

http://duckwater.bu.edu/lc/mod12q1.html and the Latin American region was extracted for further analysis.

Assessment

Accuracy assessment is a critical component of any method to generate spatial information, but it has been greatly emphasised in studies based on remotely sensed images (Congalton & Green, 1999). Most local studies include sound procedures to validate the results, based on field sampling or higher spatial resolution imagery (Barret & Curtis, 1999). However, this task is especially complex when generating global products, since it involves covering large areas with a wide diversity of potential errors. However, the importance of validating global variables is acknowledged by most global scope projects, and network of scientists are build upon those projects to assure some type of quality checking. For instance, the MODIS program has a specific task group dedicated to product validation (Morisette *et al.*, 2002)), and the team involved in the MODIS burned land product has already produced an extensive validation protocol for some study sites within the SAFARI campaign (Roy *et al.*, 2005a). In burned land mapping, neither the GBA2000 nor the Globscar project have undertaken a full validation strategy, although some efforts have been proposed for retrospective validation (Boschetti *et al.*, 2006).

The AQL2004 project was designed by a network of local scientists, and therefore, product validation was considered from the beginning of the project a priority. Considering the financial constraints of the project, the validation was based on medium resolution satellite images that were donated by regional space agencies. The Argentinean agency CONAE, the Brazilian agency INPE and the Mexican agency Conabio provided Landsat, CBERS and SPOT data for the validation of the burn scar product. Figure 2 shows the images that were used for validation of the whole project.

The validation itself was based on visual interpretation of those higher resolution images from which fire perimeters were derived. The images were previously converted to the Goode Homolosine Projection, to match the MODIS input data. Visual analysis has been widely used for discriminating burn scars (Roy *et al.*, 2005a), since burned areas generally have a distinct colour and shape pattern. Visual interpretation was digitized on screen and vector files were extracted to cross-tabulate with results from our burned land algorithm to generate confusion matrices (agreement between the results

and the validation data). Common measures of accuracy and error (omission and comission errors, and produced and user accuracies: Congalton & Green, 1999) were computed.

Considering the differences in spatial resolution between the two sets of images (MODIS and TM/ETM/CBERS), the interpretation of the confusion matrix must be done cautiously, since some errors may in fact be caused by misregistration or simply by coarser pixel size. To reduce the impact of these effects, another validation strategy was carried out by comparing the total burned area by the two satellite sources (MODIS and high-resolution images), using grid cells of 5x5 km. This approach was previously suggested by other authors (Roy *et al.*, 2005a) and provides a spatial statistical assessment of the agreement between the two data sources.

In addition to comparing our results with higher spatial resolution data, the results were also compared to the active fires detected by the MODIS program. Although they are produced by the same sensor, active fire products have no relation to burned land products, because they are based on a completely different physical principle (Justice *et al.*, 2002). Active fire detection is based on middle infrared bands, which are the most sensitive to detect high-temperature targets, and therefore the fires are only detectable when they are active, while burned land maps are based on post-fire conditions. Therefore, since the two products are independent, their agreement indicates a greater likelihood of accuracy (Roy *et al.*, 2005b). For this project, all active fires detected by the MODIS program (Giglio *et al.*, 2003) were downloaded (http://maps.geog.umd.edu/firms/shapes.htm), and referenced in 25x25km cell sizes. The number of active fires per month was compared with the total burned area discriminated by our algorithm. A total number of 29175 cells were obtained for South America and 5174 for Mexico and Central America, after removing those where water covered more than 95% of the cell area.

RESULTS

Geographical analysis of burned areas

Figure 3 includes the summary of the project results, with the total number of burned land polygons discriminated in the different periods of the MODIS 32-day composites. A total number of 14 446 burned land polygons were identified by the AQL2004 algorithm, which covered an area of 153 215 km^2. The most affected countries were Argentina, Brazil, Colombia, Bolivia and Venezuela, which sum up 90% of total area burned. In relative terms, the AQL2004 results show that the most affected

countries were Cuba, Colombia, Bolivia, Venezuela and Argentina, all presenting more than 1.2% of the national territory burned. The most continuous areas affected by biomass burnings are the savanna regions of Colombia and Venezuela, the boundaries of the evergreeen forest in Brazil and Bolivia, and the Central and Northern provinces of Argentina. Central Cuba and the Southern part of Guatemala were also noticeable. Scattered patches were observed in Mexico and Chile.

The burned areas affected a wide variety of land cover types, but the herbaceous areas presented a much higher impact. In fact, grasslands, woody savannas, and savannas summed up 63% of the total burned area in Latin America. For these categories the fire affected around 1.5% of the total area they cover in the continent. Only croplands presented a higher proportion, with more than 2%. The Evergreen forest showed the higher ratio between the percentage of total area covered in the continent and the proportion of total burned area (36/7.22), while the lower ratio was found for croplands and grasslands (8.04/17.21). This ratio implied that the proportion of burned area in evergreen forest was much lower than the total proportion of area covered by this category, being the opposite in the case of grasslands. In other words, biomass burning had much less impact in evergreen forest than in grasslands.

Seasonal trends

Biomass burning in Latin America followed seasonal dry periods in 2004, as it might be expected. Grasslands and herbaceous in the Northern Hemisphere are burned mainly between January and middle of March, while in the Southern Hemisphere the peak of fire occurrence was observed between July and September (figure 3). Seasonal distribution of burned areas for the most affected countries can be observed in figure 4. A clear peak during the dry season is observed for Colombia and Venezuela in the Northern Hemisphere, and Brazil and Bolivia in the Southern Hemisphere. Mexico had low fire occurrence in 2004, and the most affected months do not clearly match the driest periods. Argentina presents an unexpected pattern too, since most burned areas are reported between March and June.

The most common land covers in burned areas are shown in figure 5 for the different periods of analysis. The impact of fire on herbaceous vegetation was distributed throughout the year, although in the dry season (February in the Northern Hemisphere and August-September in the Southern Hemisphere) it accounted for even a larger proportion. An important percentage of the burned land

was found in agricultural areas (17%). Shrubs were found dominant in 8% of the burned area and they were distributed similarly throughout the year. The forested areas covered almost 10% of the burn scars, with more dominance of the evergreen forest. However, important proportions of deciduous forest were also found in July and September.

Assessment

Validation of the AQL2004 algorithm results were performed with both higher resolution data and active fires detected by the thermal channels of the MODIS instrument. Table 4 includes observed commission and omission errors for burned land discrimination using higher resolution images (Landsat or CBERS). Both the omission and comission errors of burn scars were relatively high in most study areas, with higher values in the central regions of Argentina, and lower in Central Brazil and Colombia. Areas covered by herbaceous vegetation offered the highest accuracies (between 85 and 70%), while croplands and sparse vegetation areas presented the lowest accuracy (between 30 and 5%). Potential errors of the algorithm in these areas should be associated to seasonal changes in croplands, specifically to the changes from green areas to dark soils as a result of harvesting.

Table 5 presents the relationship between the distribution of errors and land cover types for four different validation sites. It can be observed that the agreement between MODIS and higher resolution images was related to land cover type, with higher agreement for savannas and forested areas and lower for agriculture. Regional variation was also observed. For instance, grasslands offered higher agreement in tropical regions of Colombia and Brazil than in temperate areas of Argentina; although the amount of burned area in herbaceous vegetation is also lower in this latter region. Total accuracy, as defined by both the burn and unburned area discrimination was acceptable in all study sites. The extension of unburned areas that were properly discriminated as such increased considerably the accuracy values. It is important to remark that omission and commission errors were generally balanced in the different study areas, which made it possible to obtain more confident area estimations.

The spatial relationship between MODIS and high resolution data can be observed in figure 6, which shows two examples of the spatial validation procedure. A cross-tabulation between burn scars discriminated in the MODIS and the high resolution images made it possible to analyse the spatial disribution of agreements and disagreements between the two sources As it can be observed in

figures 6a and 6c, the disagreements are spatially contiguos with the matched pixels, and therefore errors are more related to boundary effects than to lack of proper discrimination. The scatterplots with the proportion of burned areas in both high and low resolution data for different 5x5 km cells (figures 6b and 6d) provided a complementary view of the spatial agreements, between the two data sources. The distribution of burn land proportion for the two study cases shown had a clear agreement between the two datasets, with r^2 of 0.35 in the Colombian image and 0.75 in Brazil. In other study areas the correlations found within similar ecosystems were comparable with those. However, for the Southern part of Argentina they were much lower, below 0.2.

The final validation exercise was focused on comparing burn scars and active-fires. A 25x25km grid cell was used in this case for extracting both sources of fire information. The proportion of pixels within each cell in both sources was correlated for the whole continent. Table 6 offers the results for South America and Mexico. The trends show a global tendency of agreement between the two data sources with positive correlations for most periods. The average correlation between the two sources of data was 0.229 ($p<0.001$). The peaks of fire occurrence, in January-February and August-September offered also the highest correlations, especially the former. In Central America, the correlations were generally lower (0.1 was the annual average). Differences in agreement values were observed between different land covers. Grasslands presented the highest correlations in the dry periods of both Hemispheres, while forested areas and crops offered low accuracy at the beginning of the year to peak in February and June. Shrubs showed better r correlation at the beginning of the time series, but show poor agreement.

DISCUSSION AND CONCLUSSIONS

The AQL2004 project generated a burned land map of Latin America for 32-day periods covering 2004. The total estimation of burned area for the continent (153 215 km^2) was similar to that obtained through similar projects for 2000, when the GBA2000 project estimated 137 000 km^2 and GLOBSCAR 162 774 km^2, as well as with the average Burneo area calculated for the 1997-2004 period from active fire detections (200 000 km^2: (van der Werf *et al.*, 2006). To obain similar estimations, in spite of using very different sensors (SPOT/VEGETATION for the GBA2000 project and ATSR for GLOBSCAR) or different data sources (active fires in the van der Werf et al.'s study), confirms the robustness of the burned area estimations.

At local scale the estimations should be taken with more caution, according to the accuracy assessment obtained and the work of other authors. For instance, Armenteras et al. (2005) found the burned area to be about one third of the AQL2004 estimation in their estimations of 2000 and 2001 of the Colombian savannas using Landsat images, although their data do not refer to the whole country, as the AQL2004's does. In any case, their study showed a similar temporal pattern as the one found for AQL2004 data.

The case of México requires a further examination, since it offered very low burned areas comparing to the size of the country. Although national statistics do not match AQL2004' estimations in absolute numbers, they clearly show a decrease in fire activity for 2004. In fact, that year had the lowest fire occurrence in México in the period 1998 to 2005, according to the Mexican Forest Service (Conafor, personal communication). This was caused by humid conditions, especially at the beginning of the year. The seasonal trends of expected fire occurrence did not agree with the observed trends, since in Mexico the burned land areas were mainly detected during the Fall, which is ordinarily wetter than early Spring, although the particular weather patterns of 2004 were not available for validation this hypothesis. Confusion between agricultural crops and wildland fires may explain this temporal trend, since many burn scars were located in burned areas. However, there is not much information on agricultural burnings in the country.

The validation of the results was done with three different methods, that generally agreed, although various uncertainties in the data preclude deriving final conclusions on the validation exercise. On one hand, the comparison of high resolution data (Landsat or CBERS) with MODIS data implies potential problems caused by misregistration or boundary effects. On the other hand, Landsat images did not match the MODIS 32-day composites periods, so it was difficult to assess whether for instance omission errors may be in fact so, or may be fires that occurred between the Landsat image acquisition and the end of the 32-day composite period, in case of using a Landsat image from after the end of the composite period. An opposite situation would occur when the Landsat image was acquired within the 32-day composite period, but in this case it would affect the commission errors. Finally, the relation between hot-spots and burn scars improved the spatial analysis of errors, but it can no be properly considered a reliable validation neither, since active fire detection refer to the specific time of the satellite overpass (regularly around 14 h in the Equator), and it may missed those that occurred at night or under a dense canopy. However, the global correlation between the two

sources can be considered quite relevant for the AQL2004 project (0.229), specially if it is compared with other products. For instance, Boschetti et al., (2004) computed for the Latin American region a Pearson r value of 0.013 between the results of the GBA200 burned land areas and active fires derived from ATSR. The r value was even lower for the relationship between GLOBSCAR and ATSR (-0.003). As a result of the three validation methods used in this paper, it can be concluded that global accuracy can be considered acceptable.

However, for local regions, the validation exercise also showed that additional efforts are required to adapt the global algorithm to specific land cover or climatic regions, as well as to explore potential improvements with other standard MODIS products. The main potential sources of errors for the AQL2004 project can be related to the limitations of input data, the global character of the algorithm and the local ecological diversity. The main limitations of the 32-day MODIS composites for this project should be associated to the length of the compositing period, which may fade the spectral signature of burned areas especially in grassland regions, and the effects of cloud contamination and view and illumination angle effects. The former limitation has been observed in other studies from tropical regions, where the carbon signal has almost disappear with few weeks after the fire (Armenteras *et al.*, 2005; Trigg & Flasse, 2000). Regarding the angular effects on the 32-day MODIS composite, the use of the MOD43 product, which include a BRDF correction, may be more advisable as it has already observed by other authors (Roy *et al.*, 2005b).

Development of local algorithms is another line of potential improvement of the AQL2004 project. The results from Mexico and the Patagonia, for instance, show a clear room for developing thresholds or new spectral indices that may be better adapted to the particular soils or vegetation characteristics of the region. Preliminary analysis in Patagonia and Central Buenos Aires in Argentina show better results that those obtained with the global AQL2004 algorithm, but they can not easily be generalized.

The AQL2004 project has provided a sound product for ecological and atmospheric scientists while making it possible to build a collaborative network with very limited funding.

The importance of having a systematic evaluation of burned areas in the continent has already been commented. From a global emission estimation point of view, Latin America during the period 1997-2004 accounted fro 5.81% of total Burneo area and 15.77% of total biomass burning carbon emissions, and it had more than three times higher emission ratio than Africa for the same period (van der Werf *et al.*, 2006).

On the other hand, wildland fires are still the main factor of land use change in the continent. Fire is used to remove vegetation in the first phase or after logging, then causing a permanent degradation in many areas previously covered by evergreen forest ((Cochrane *et al.*, 1999)).

Finally, the ecological impacts of fire need to be addressed at global and local scales, by improving current fire history estimates and spatial distribution of burned areas. The effects of fire on biodiversity and soil degradation have been emphasised by several authors (Siegert *et al.*, 2001; van Nieuwstadt *et al.*, 2001), especially when the natural fire regimes are shortened. Therefore, to get a better knowledge of those fire regimes is critical to assess fire impacts at medium and long-term temporal scales, and the better understand the role of fire in current landscape spatial structure (Vega-Garcia & Chuvieco, 2006). The AQL2004 project has shown a great potential to provide input data to undertake these ecological analysis.

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Table 1: MODIS spectral bands of the 32-day reflectance composite

Number	Wavelength (nm)	Spectral region
1	620-670	Red
2	841-876	Near infrared
3	459-479	Blue
4	545-565	Green
5	1230-1250	SWIR
6	1628-1652	SWIR
7	2105-2155	SWIR

Tabla 2: Thresholds to determine burn land core pixels in the first phase of the mapping algorithm

Variable	Threshold value
Post-fire image:	
BAI MODIS	> 99
NBR	> 0
Multitemporal change:	
BAI $MODIS_t$ - BAI $MODIS_{t-1}$	> 1.74
NBR_t – NBR_{t-1}	> 0.35

Table 3: Burned areas mapped in the AQL2004 project in the different 32-day periods (InitialDayMonth/FinalDayMonth).

Country	**2712/0102**	**0202/0403**	**0503/0504**	**0604/0705**	**0805/0806**	**0906/1007**	**1107/1108**	**1208/1209**	**1309/1410**	**1510/1511**	**1611/2512**	**TOTAL**
Argentina	542.00	1356.50	2953.00	6850.75	6802.50	7285.00	2700.75	1700.38	3320.50	667.25	999.63	35178.25
Belize	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.63	0.00	10.63
Bolivia	41.50	155.50	29.25	107.25	98.13	265.25	2138.50	5631.50	6453.00	1273.75	80.00	16273.63
Brazil	298.38	331.75	2135.00	2011.88	2010.13	5233.00	9744.25	12509.88	12686.75	4610.88	1559.50	53131.38
Chile	56.00	256.38	670.88	312.38	108.88	66.13	18.13	79.63	222.50	62.00	68.50	1921.38
Colombia	4531.50	12788.63	1602.38	0.00	0.00	85.63	32.00	85.25	134.13	10.00	179.75	19449.25
Costa Rica	0.00	14.50	33.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	48.25
Cuba	1261.25	644.62	1051.50	53.63	0.00	0.00	18.75	0.00	0.00	120.38	170.00	3320.12
Dominican Republic	23.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	23.25
Ecuador	18.25	0.00	12.88	11.50	0.00	0.00	13.75	0.00	31.00	28.25	0.00	115.63
El Salvador	29.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	21.00	50.50
Guatemala	263.25	159.00	39.75	0.00	0.00	0.00	0.00	0.00	0.00	23.88	182.13	668.00
Guyana	54.38	25.50	0.00	0.00	0.00	0.00	0.00	10.63	0.00	83.13	158.50	332.13
Haiti	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	17.13	0.00	17.13
Honduras	22.63	0.00	19.63	0.00	0.00	0.00	0.00	23.50	0.00	0.00	41.63	107.38
Mexico	233.87	89.13	261.88	160.50	19.25	31.63	105.88	61.63	1906.50	1295.00	663.88	4829.13
Nicaragua	223.13	39.50	19.38	0.00	0.00	0.00	26.00	0.00	0.00	9.13	29.50	346.63
Panama	0.00	0.00	0.00	0.00	0.00	12.88	0.00	0.00	0.00	0.00	0.00	12.88
Paraguay	45.63	752.88	876.88	24.25	24.25	161.50	57.25	518.13	1411.38	460.50	0.00	4332.63
Peru	28.13	11.63	22.75	16.00	14.63	13.63	9.00	19.50	28.25	19.00	5.25	187.75
Suriname	0.00	11.50	9.50	0.00	0.00	0.00	0.00	0.00	38.63	7.75	14.00	81.38
Trinidad and Tobago	0.00	8.00	8.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	16.00
Uruguay	6.38	12.00	66.63	9.00	9.00	6.63	37.13	29.63	33.75	23.63	26.50	260.25
Venezuela	3567.13	6384.25	2040.63	0.00	0.00	41.25	0.00	0.00	0.00	54.50	413.50	12501.25
Total	11246.12	23041.25	11853.63	9557.13	9086.75	13202.50	14901.38	20669.63	26266.38	8776.75	4613.25	153214.75

All values are in square km

Table 4: Commission and omission errors for burned land estimation, as well as global accuracy for several validation sites

	Burned Area Errors		Total Errors
	Comission Error	Omission Error	
Colombia February	48.219	55.270	15.887
Colombia January	39.403	81.234	7.613
Brazil-Bolivia August	14.921	45.248	7.425
Argentina August	54.744	29.569	2.026
Mexico - May	14.124	55.815	0.026
Mexico - March	55.623	47.482	0.038
Mexico - April	69.934	42.092	0.083
Argentina February	72.356	95.375	0.448
Argentina November	83.426	94.027	2.709

Table 5: Relations between errors and land cover types.

Error Type	**Validation Zone**	**Agriculture**	**Grassland**	**Shrublands**	**Forested areas**
Omission	North cod-12	0.0006	0.9793	0.0037	0.0103
Error	North cod-21	0.0182	0.8299	0.0811	0.0705
	Central cod-52	0.0520	0.3664	0.2144	0.3054
	Central cod-62	0.0617	0.0411	0.1028	0.6786
	Total	0.0331	0.5542	0.1005	0.2662
Burn Area	North cod-12	0.0004	0.9851	0.0019	0.0085
Coincidence	North cod-21	0.0077	0.9230	0.0422	0.0115
	Central cod-52	0.0634	0.2459	0.3060	0.3404
	Central cod-62	0.1468	0.0691	0.0518	0.7770
	Total	0.0545	0.5558	0.1005	0.2843
Commission	North cod-12	0.0025	0.9776	0.0037	0.0219
Error	North cod-21	0.0059	0.9119	0.0443	0.0266
	Central cod-52	0.0674	0.2265	0.3368	0.4041
	Central cod-62	0.2141	0.0714	0.2284	0.4782
	Total	0.0725	0.5469	0.1533	0.2327

Table 6: Pearson r correlation values between burn scars and active fires for the different study periods.

	South America					Mexico
Period	Forest	Shrubs	Grasslands	Crops	All covers	All covers
2712-0102	0.045	0.376	0.492	0.035	0.367	0.020
0202-0403	0.265	0.450	0.453	0.423	0.383	0.236
0503-0504	0.071	0.119	0.309	0.096	0.233	0.069
0604-0705	0.033	-0.002	0.103	-0.042	0.022	0.056
0805-0806	0.173	0.173	0.131	-0.027	0.042	0.077
0906-1007	0.203	0.137	0.273	0.368	0.195	0.057
1107-1108	0.227	0.062	0.293	0.301	0.170	0.000
1208-1209	0.331	-0.032	0.404	0.083	0.149	0.119
1309-1410	0.190	0.048	0.221	0.054	0.184	0.240
1510-1511	0.130	-0.002	0.062	0.015	0.066	0.160
1611-2512	0.119	0.130	0.069	0.040	0.065	0.237

Figure 1: Effect of changing window size in the regional context algorithm. a) 3x3 pixel b) 21x21

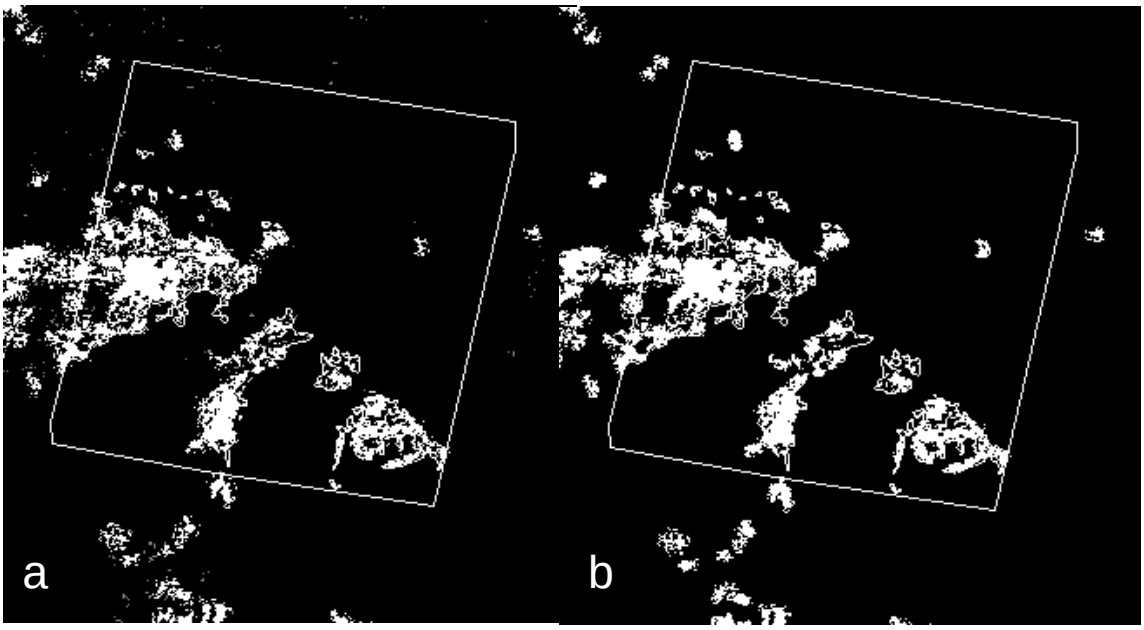

Figure 2. Validation sites where high resolution satellite data was processed

Figure 3: Geographical distribution of burn scars for the different MODIS 32-day composites.

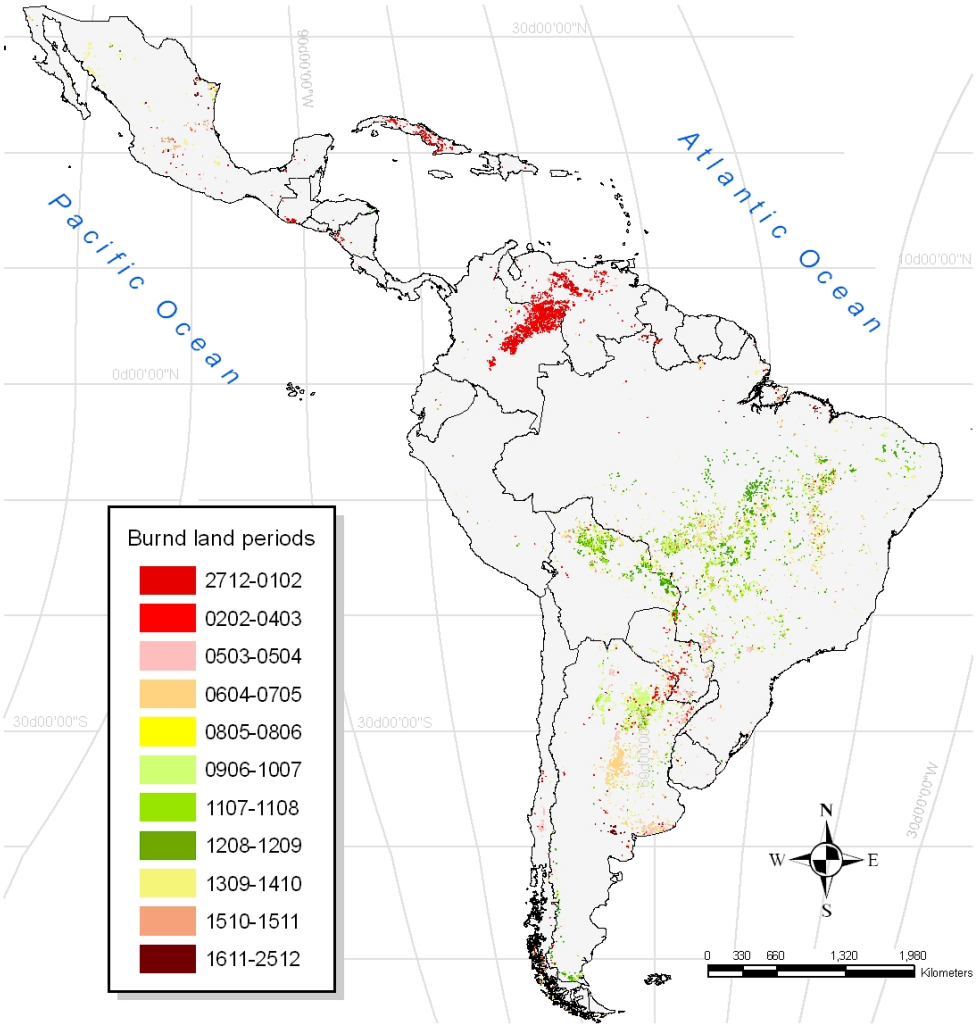

Figure 4: Seasonal distribution of burned areas for different Latin American countries (all areas in sq km)

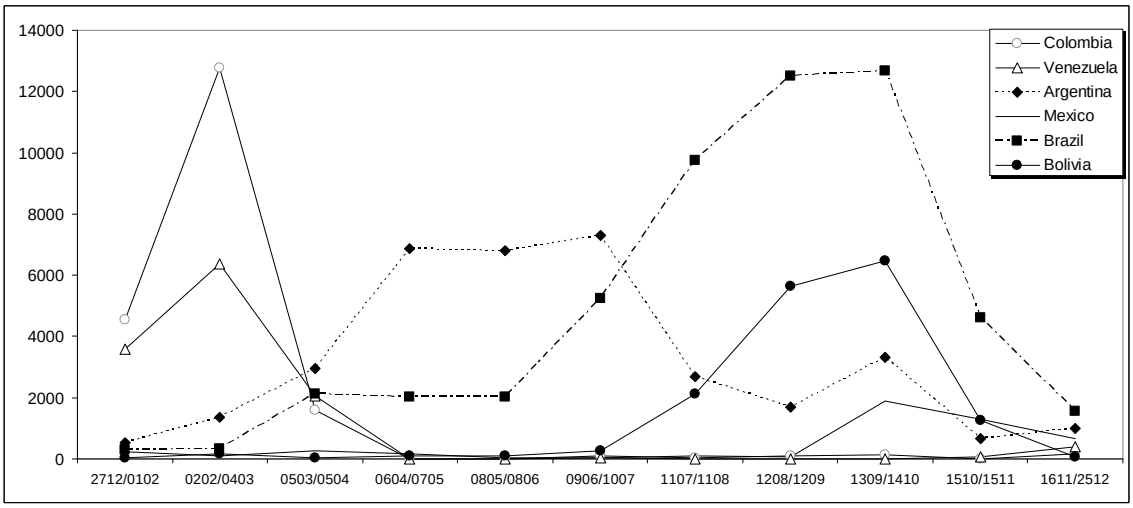

Figure 5: Monthly burned areas for different land covers (all areas in sq km)

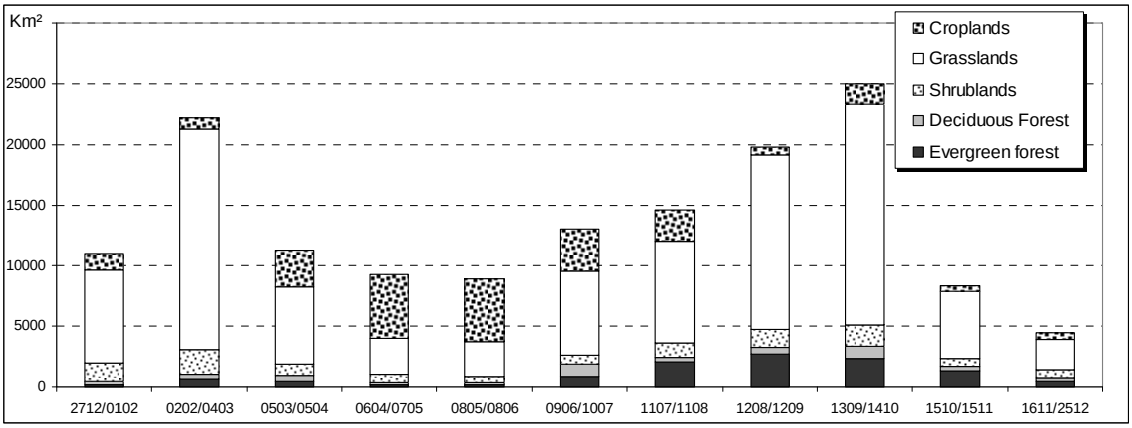
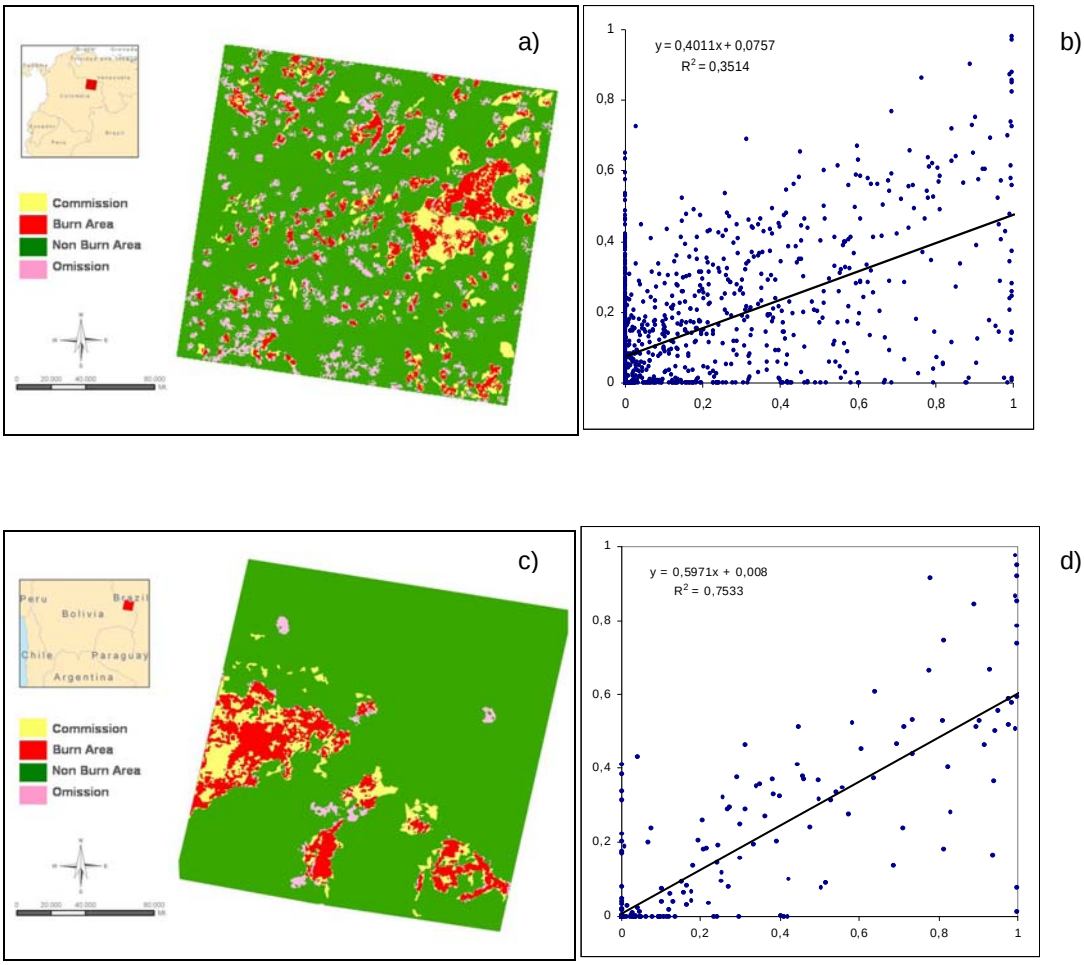
Figure 6: Two examples of the validation procedure: a) and c) cross-tabulated images of burned areas in Landsat and MODIS; b) and d) scattergrahs derived from 5x5 km grid with the proportion of burned area identified by both sources. Site a/b) is Eastern Colombia; site b/d) is Western Brazil.