A SAR FINE AND MEDIUM SPATIAL RESOLUTION APPROACH FOR MAPPING THE BRAZILIAN PANTANAL

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Abstract

The objective of this research was to utilize a dual season set of L-band (ALOS/PALSAR) and C-band (RADARSAT-2 and ENVISAT/ASAR) imagery, a comprehensive set of ground reference data, and a hierarchical object-oriented approach to 1) define the diverse habitats of the Lower Nhecolândia subregion of the Pantanal at both a fine spatial resolution (12.5 m), and a relatively medium spatial resolution (50 m), thus evaluating the accuracy of the differing spatial resolutions for land cover classification of the highly spatially heterogeneous subregion, and, 2) to define on a regional scale, using the 50 m spatial resolution imagery, the wetland habitats of each of the hydrological subregions of the Pantanal, thereby producing a final product covering the entire Pantanal ecosystem. The final classification maps of the Lower Nhecolândia subregion were achieved at overall accuracies of 83% and 72% for the 12.5 m and 50 m spatial resolutions, respectively, defining seven land cover classes. In general, the highest degree of confusion for both fine and medium resolution Nhecolândia classifications were related to the following issues: 1) scale of habitats, for instance, *capões*, *cordilheiras, and lakes,* in relation to spatial resolution of the imagery, and 2) variable flooding patterns in the subregion. Similar reasons were attributed to the classification errors for the whole Pantanal. A 50 m spatial resolution classification of the entire Pantanal wetland was achieved with an overall accuracy of 80%, defining ten land cover classes. Given the analysis of the comparison of fine and relatively medium spatial resolution classifications of the Lower Nhecolândia subregion, the authors concluded that significant improvements in accuracy can be achieved with the finer spatial resolution dataset, particularly in subregions with high spatial heterogeneity in land cover.

Key-words: Radar imagery. Pantanal. Habitat. Spatial resolution. Object-oriented classification.

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Resumo

Mapeamento do pantanal brasileiro utilizando imagens de radar de abertura sintética em resolução especial alta e média

O objetivo deste trabalho foi utilizar um conjunto de imagens de radar banda L (ALOS/PALSAR) e banda C (RADARSAT-2 e ENVISAT/ASAR), um conjunto de dados de referência de campo robusto, e o método de classificação orientado ao objeto para (1) definir os habitats da sub-região da Baixa Nhecolândia do Pantanal em alta (12.5 m) e médiaresolução espacial (50 m), permitindo assim avaliar a acurácia da classificação em relação a resolução das imagens; e (2) definir em uma escala regional, resolução de 50 m,oshabitats de cada sub-região do Pantanal. Os mapas resultantes da classificação para a baixa Nhecolândia apresentaram um acurácia de 83% e 72% para as resoluções de 12.5 m and 50 m, respectivamente, considerando um total de sete classes. A análise das classificações demostrou que a maior percentagem de erro acorreu devido 1) ao tamanho das unidades da paisagem, por exemplo, *capões*, *cordilheiras* e lagos, em relação a resolução espacial das imagens; e 2) a variabilidade espacial da inundação na sub-região. Razões similares podem ser atribuidas ao erro da classificação do Pantanal inteiro. Para esta classificação, a acurácia final foi de 80%, considerando 10 classes. Erros ocorreram predominantemente entre classes que são representadas por uma diferente composição de, por exemplo, herbaceas e floresta; nestes casos, uma definição arbitrária de classes de acordo com o gradiente de biomassa pode resultar em erros na classificação. A análise final sugere que aumento naacurácia da classificação da cobertura do solo do Pantanal requer imagens de alta resolução espacial, especialmente em sub-regiões de alta heterogeneidade da paisagem.

Palavras-chave: Imagens de radar. Pantanal. Habitats. Resolucão espacial. Classificação orientada a objeto.

INTRODUCTION

Analog aerial photography has been used for the purposes of defining wetland areas since the 1970’s (Howland, 1980; Polis et al., 1974), and presently, it is still considered a relatively reliable medium for obtaining high resolution coverage for localized, small-scale mapping purposes (CARPENTER et al., 2011; Wilen et al., 1999) and for historical wetlands mapping looking at change detection for which no satellite data exists (CSERHALMI et al., 2011). However, aerial photography is expensive to obtain over large areas, and so is also only practical for smaller scale mapping efforts. As an alternative, satellite remote sensing presents a cost effective, efficient, and practical approach that can be used to map wetland habitats across a diverse range of scales, with advantages that include multi-spectral and multi-temporal data collection (RUNDQUIST et al., 2001; OZESMI; BAUER, 2002; REBELO et al., 2009).

Specifically in the Pantanal, various remote sensing methods have been used to map features of the landscape. For example, different researchers have used satellite imagery to map the subregions of the Pantanal, but the resulting classification maps have been restricted to 1) a single habitat, such as lakes in the Nhecolândia subregion (NOVACK et al., 2010); or 2) a single subregion or a small subset at a local scale (ABDON et al., 1998; GALVÃO et al., 2003; COSTA; TELMER, 2006, 2007; NOVACK et al., 2010; ARIERA et al., 2011; EVANS; COSTA, 2013). Large scale classifications of the entire Pantanal have been done, but were limited to a coarse spatial resolution (EVANS et al, 2010). GEF (2004) and PROBIO (2007) both produced 30 m spatial resolution classifications based on optical imagery of the Pantanal, however, imagery was acquired over a time span of approximately five years due to frequent cloud cover in the region, particularly during the wet season (December to May). The primary differences among the above cited research in the Pantanal rely on the different remote sensing technologies, optical or synthetic aperture radar (SAR), and on the temporal and spatial scale of the imagery.

The use of SAR imagery has long been recognized as an important tool for studying tropical wetlands, largely because of the noticeable difference between the signal recorded from dry and flooded vegetation, the ability to detect ground signal even under significant cloud cover conditions, and the ability to penetrate the vegetation canopy (DOBSON et al., 1996; KASISCHKE et al., 1997). The SAR signal offers information about the target based primarily on canopy biophysical characteristics and dielectric properties, rather than biochemical and morpho-anatomical features as observed by optical systems (HENDERSON; LEWIS, 2008).The ability to detect ground signal even under cloudy conditions allows acquisition of useful SAR imagery at the same scale as the temporal resolution of the satellite; the same cannot be assumed for optical imagery acquisition. This is an important attribute of SAR imagery when the goal is to derive land cover maps of wetlands with characteristic temporal flood dynamics because ecological phenomena may show seasonal, annual, or even decadal cycles of change (EVANS et al., 2010; SILVA et al., 2010).

In the spatial domain, one must consider the spatial resolution of the remotely sensed imagery, the extent of the study area (BENSON; MACKENZIE, 1995), and the size of the minimum area of interest (ANDERSON et al., 1976). Landscapes that are highly heterogeneous in nature must be delineated at a finer spatial resolution, or the subsequent classification could overlook significant landscape features (BENSON; MACKENZIE, 1995). The challenge of using fine spatial resolution data arises when the objective is to map large areas, thus requiring several contiguous satellite imagery frames with temporal discontinuity between image dates, as inconsistent moisture conditions and/or phenological differences of just a few weeks can exhibit considerable radiometric differences (LOWRY et al., 2007, LUCAS et al., 2010).

The objective of this research is to evaluate the land cover classification products derived from SAR imagery at 12.5 m and 50 m spatial resolutions for the Lower Nhecolândia subregion of the Pantanal, and further evaluate the 50m resolution product derived at a regional scale for the entire Pantanal. Issues related to imagery spatial resolution and land cover spatial heterogeneity will be discussed.

SAR INTERACTIONS IN TROPICAL WETLANDS

SAR systems operate in the microwave region of the electromagnetic spectrum, with wavelengths commonly coded by a single letter: X (3cm); C (5.6cm); S (10cm); L (23cm); and P (75cm) (OLIVER; QUEGAN, 2004). The main scattering mechanisms typical in L and C bands are illustrated in Figure 1. Generally, longer wavelengths allow deeper canopy penetration and are less sensitive to smaller biophysical variations. With L-band SAR data, smooth surfaces such as flat water or bare soil, or even relatively short vegetation (< 23cm wavelength of L-band) such as pasture, will specularly reflect most energy; when surface roughness is increased, as happens with the addition of taller vegetation, backscattered radiation also increases (ULABY et al., 1981). When the forest floor is non-flooded, there is volumetric scattering happening within the forest canopy and at the ground level, depending on the height of the understory. Double-bounce reflection is caused by the interaction of the incident energy with the tree trunk (or any structure perpendicular to the surface) followed by a change in direction towards a specular surface (typically bare soil, very short vegetation, or water), where energy is reflected back towards the sensor; this process also happens in the opposite direction (ULABY et al., 1981). Once the area is flooded, even shallowly, there is a strong double-bounce reflection between the tree trunks and the water surface, adding to the volumetric scattering within the canopy, and greatly enhancing the return signal to the sensor (ROSENQVIST et al., 2007).

The main scattering processes are the same for C-band as for L-band; however the interactions between the incident radiation and specific cover types vary due to the shorter wavelength of C-band (5.6 cm). For example: the shorter wavelengths of C-band do not allow for the penetration of dense forest canopy, therefore the majority of backscattering for this cover type results from volumetric scattering within the canopy; short vegetation, such as pasture, that may not be visible at the longer wavelengths due to specular reflection, will provide a moderate backscattering return, also resulting from volumetric scattering (Figure 1); C-band double-bounce has been reported for vertical herbaceous vegetation such as *Typha sp*. (COSTA; TELMER, 2006; POPE et al., 1997).

A combination of L and C-band SAR imagery has been employed for many wetland studies (WANG, 1994; HESS et al., 1995, 2003; POPE et al., 1997; COSTA et al., 2002; COSTA; TELMER 2006, EVANS et al., 2010). C-band has been found to have the highest accuracies for delineating sawgrass and cattail marshes, and for classifying other herbaceous wetlands (POPE et al., 1997; KASISCHKE, 1997). Furthermore, an increase in signal due to double-bounce has been reported for aquatic macrophytes in standing water at shorter C-band wavelength (BROWN et al, 1996; POPE et al., 1997). In general, longer wavelengths (L-band) are preferred for detection of inundation for forested wetlands, and shorter wavelengths (C-band) are suggested for herbaceous wetlands. However, current research suggests that a combination of both bands and polarizations is beneficial for a comprehensive understanding of complex wetland dynamics (SCHMULLIUS; EVANS, 1997; COSTA, 2004; COSTA; TELMER, 2006; HENDERSON; LEWIS, 2008).

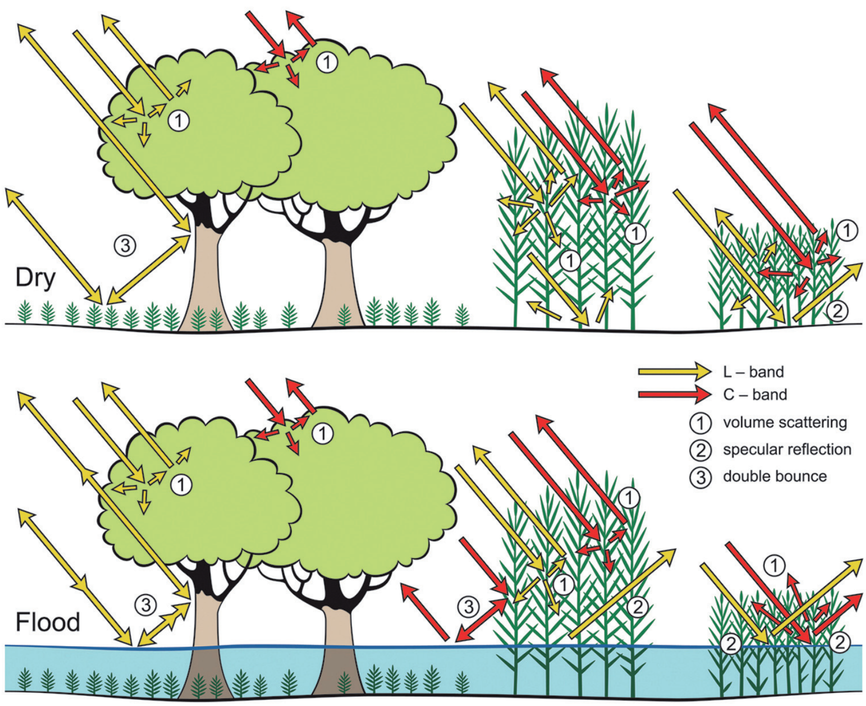

Figure 1 - C and L-band SAR interactions in tropical wetlands

METHODS

Study area

The Pantanal is one of the largest and most important tropical wetlands globally, with estimates suggesting that the total area subject to seasonal inundation covers approximately 160,000 km^{2}in wetter years, within a broader watershed occupying an area of approximately 362,000 km^2 (JUNK et al., 2006). The drainage network and the rainfall patterns of the Pantanal support a seasonal, often monomodal flood regime that varies both temporally and spatially, thus delineating several subregions with diverse characteristics in terms of ecology, hydrology and geomorphology. This flood regime is the key driver of the high habitat diversity of the Pantanal (JUNK et al., 2006; MAMEDE; ALHO, 2006).

Hamilton et al. (1996) divided the Pantanal into ten subregions: Corixo Grande (CORI), Paraguay (PARA), Cuiaba (CUIA), Piquiri/ São Lourenço (PIQU), Taquari Fan (TAQF), Taquari River (TAQR), Nhecolândia (NHEC), Aquidauana/Negro (AQUI), Miranda (MIRA), and Nabileque (NABI) based on hydrology and geomorphology. Generally, in the Pantanal, the intensity of the inundation regime in these subregions increases from east to west and from north to south (HAMILTON et al., 1996). The majority of the subregions are under the influence of rivers with peak discharge generally from January to March; exceptions are the Paraguay and Taquari rivers subregions under the influence of the Paraguay River with peak discharge from May to June, and the Nabileque subregion under the influence of the southern Paraguay River with peak discharge generally between July and August (HAMILTON et al., 1996; ANA, 2010)

Specifically, the Lower Nhecolândia subregion of the Pantanal is characterized by medium height/medium duration partial and localized flooding, with high waters typically occurring from February to April, and low waters from August to November (HAMILTON et al., 1996). This region is also characterized by an abundance of small lakes/ponds (POTT; POTT, 2011a), and a highly heterogeneous landscape, with forest, savanna, wild grasslands, introduced pastures, seasonal waterways, herbaceous vegetation, and aquatic macrophytes.

Field data

A comprehensive ground reference database including latitude/longitude coordinates, dominant vegetation description, reference notes, and in many cases, photographs were acquired for the entire Pantanal. A total of 599 reference sites were defined for the entire Pantanal. From these, 223 ground reference sites were localized in the Nhecolândia (NHEC), Aquidauana/Negro (AQUI), and Miranda (MIRA) subregions, and 376 ground reference sites covered the other subregions. The ground reference sites were organized according to a defined classification scheme to represent habitats described for the region (POR, 1995; POTT; POTT, 2000, 2011a, 2011b; CAMPOS FILHO, 2002; NUNES DA CUNHA et al., 2007; NUNES DA CUNHA; JUNK, 2011; Pott et al., 2011), and distinguishable with the SAR imagery. Defined habitats are as follows: (1) forest woodland, which includes deciduous and semi-deciduous forest, *cerradão*, *cordilheiras*, and *capãos*; (2) riparian forest, which includes dense fluvial forest adjacent to rivers; (3) open wood savanna, which includes mixed vegetation with shrubs and short scattered trees on a grassy stratum; (4) open wood savanna - flood, which is generally characterized by monodominant stands of woody vegetation and pioneer species, and are subjected to prolonged flooding;(5) open grass savanna (*campo sujo*), which includes dominantly grassy terrain with some scattered shrubs; (6) swampy grassland (*campo limpo* and *campinas*), which includes areas covered with grasses, herbaceous vegetation, and sedges – frequently flooded; (7) swampy mixed savanna, which includes dense mix of herbaceous, shrubs, and pioneer species – frequently flooded;

(8) agriculture, which includes cultivated pasture and crops; (9) *vazantes*, defined as seasonal drainage channels; and (10) water, which includes rivers and lakes. The following habitats are not represented in the classification of the Nhecolândia subregion: riparian forest, open wood savanna - flood, and swampy mixed savanna.

Satellite data

Fine spatial resolution – Nhecolândia subregion only: L-band images from ALOS/PALSAR were acquired for January/February 2008 (12.5m, HH polarization) coinciding with high water, and for August/September 2008 (12.5m, HH and HV polarization) coinciding with low water and the field campaign. RADARSAT-2 images were acquired for August 2008 (25m, HH and HV polarization) coinciding with low water and field campaign. Additional C-band imagery for high water was acquired in February/March 2010 from ENVISAT/ASAR (12.5m, HH and HV polarization).

Medium spatial resolution – entire Pantanal: L-band orthorectified mosaics from ALOS/PALSAR were acquired for February/March 2008 (50 m, HH polarization), and for August/September 2008 (50 m, HH and HV polarization) coinciding with the 2008 field campaign. C-band images from RADARSAT-2, were acquired for August/September 2008 (ScanSAR Narrow 50m, HH and HV polarization) coinciding with field observations.

ALOS/PALSAR images were acquired as part of the JAXA ALOS Kyoto and Carbon Initiative – Pantanal, C-band images from RADARSAT-2, were obtained as part of the Canadian Space Agency’s Science and Operational Applications Research (SOAR) program, and C-band ENVISAT/ASAR images were acquired as a part of an agreement with the European Space Agency (ESA). RADARSAT-2, ALOS/PALSAR, and ENVISAT/ASAR were requested at a pre-processed level, and already radiometrically calibrated for incidence angle and radiometric distortions (Luscombe, 2009; Shimada et al., 2009; Rosich & Meadows, 2004, respectively). Images were georeferenced and projected to UTM coordinates (zone 21, row K) using the WGS84 reference ellipsoid. Each set of images was mosaicked to form cohesive coverage of the respective study areas (50m resolution for the entire Pantanal, and fine spatial resolution for Nhecolândia only). Geometric inconsistencies were corrected using a second order polynomial approach resulting in an RMS error of <1 pixel for both the x and the y-axis in all cases. All mosaics were filtered to reduce the effect of speckle by utilizing a Kuan filter with a 3 x 3 kernel (OLIVER; QUEGAN, 2004).

OBIA Classification Steps

The classification was performed using an object based image analysis (OBIA) approach, executed using the Definiens eCognition software package (V.8.0). The OBIA approach was applied aiming to minimize the contribution of the speckle signal to the classification. The speckle signal is inherent of SAR imagery, and it is known to cause problems with pixel-based classification methods (LAUR, 1997).

Nhecolândia region – fine spatial resolution

A primary multiresolution segmentation was performed using an optimal set of parameters for creating appropriately sized image objects to represent landscape features such as small lakes as individual entities: scale = 50; shape = 0.005 (heavily emphasizing radiometry over shape); compactness = 0.5 (equal emphasis on smoothness and compactness); and, more heavily weighting the dry season imagery to better separate the lakes from seasonal flooding areas.

Training image objects were defined on the segmented layer, and selected based on approximately 50% of the ground reference data (the remaining 50% was held back for subsequent validation of the finished product). In many cases, individual ground reference points were utilized for more than one training object where photographs were available showing variable vegetation cover in different directions, or where available information expressed more than one vegetation cover (ie. "forest-grassland border").

Once training objects for each class were defined, the subsequent classification rule-set was as follows: 1) Thresholds were built for each class based on mean backscattering separability and expert knowledge; thresholds were based on more than one image (how many, and which images were decided based on the images deemed best for isolating the class from all other classes, considering band, polarization, and seasonal mean backscattering differences), and used the "AND" operator: for example threshold for class *x* = mean +/- 1 SD in image *a,* AND mean +/- 1 SD in image *b,* AND mean +/- 1 SD in image *c*. This method aided in dealing with the overlap between class object backscattering in any one particular image; 2) Utilization of a supervised nearest neighbour algorithm employing a combination of several features as primary inputs (mean, standard deviation, brightness, maximum difference, proximity, shape and compactness) using the feature space optimization (FSO) routine in eCognition Developer (V. 8. 0); 3) If confusion between two classes was still evident, subsequent iterations of the FSO routine refining the input parameters were performed. This classification approach resulted in the classification of seven land cover classes for the Nhecolândia subregion: Forest Woodland, Open Wood Savanna, Open Grass Savanna, Agriculture, Swampy Grassland, *Vazantes*, and Water.

Classification results were compared to field data held back for validation purposes. A total of 147 validating image objects were tested against field data for classification accuracy. This validation data was supplemented by a set of 150 randomly generated points across the study area (STEHMAN, 1996; SILVA et al., 2010), which were classified through visual interpretation of ALOS Advanced Visible and Near-Infrared (AVNIR-2) sensor (processing level 1B2, 10 m spatial resolution, four images acquired on January 20, 2007 and three images acquired on February 02, 2007) obtained from JAXA, Landsat ETM (30 m spatial resolution, acquired on April 2002), as well as Landsat ETM (30 m spatial resolution, acquired in December 2007) and IKONOS (4 m spatial resolution, acquired in July 2006 and 2007) imagery available in Google Earth Pro.

Entire Pantanal – medium spatial resolution

All 50 m imagery mosaics, as well as hydrological subregion vectors from Hamilton et al. (1996), and a water mask for the Nhecolândia subregion produced with the 12.5 m resolution imagery, were imported into eCognition for subsequent segmentation and classification.

The multiresolution segmentation was performed using an optimal set of parameters as follows: the scale parameter was defined as 20 to deal with the imagery spatial resolution , however the shape and compactness parameters remained the same as for the fine resolution classification – 0.005 and 0.5, respectively. Segmentation was performed giving equal weight to the wet and dry season L-band, and dry season C-band HH polarization mosaics to best exploit both the temporal differences in flooding patterns, and the unique spectral signatures of different land cover classes available with a dual-band approach. Once the segmented layer was created, all objects under the water mask were classified as "Nhecolândia – Water" and removed from further consideration.

Training objects for land cover classes for all subregions of the Pantanal were chosen based on available ground reference data (primary training objects), and expert knowledge combined with additional reference data (secondary training objects). Mean and standard deviation values for each class/subregion/band were calculated to define radiometry thresholds for each of the classes. In addition, a seasonal change detection algorithm was created in order to exploit the seasonal differences in land cover for subregions where flood and dry season roughly corresponded to the imagery acquisition. The classification rule-set followed the same three step pattern as for the fine resolution classification (1. build thresholds; 2. nearest neighbour/FSO; 3. refine rules iteratively until all objects were classified), and was conducted separately for each subregion. This classification resulted in a total of ten cover classes for the entire Pantanal: Forest Woodland, Riparian Forest, Open Wood Savanna, Open Wood Savanna – Floods, Open Grass Savanna, Agriculture, Swampy Grassland, Swampy Mixed Savanna, *Vazantes*(water ways),and Water.

Once all subregions were classified, results were compared to the 391ground reference data points held back for validation of the entire Pantanal, and reported as overall (%) accuracy.

RESULTS AND DISCUSSION

Figures 2a and 2b show the spatial distribution of land cover units for the Nhecolândia subregion of the Pantanal at fine and medium spatial resolution, respectively. Validation results for the fine and medium spatial resolution classification of this subregion are seen in Table 1a and 1b, respectively. As expected, overall accuracy is higher for the 12.5 m resolution classification product (83%) than for the 50m resolution (72%). In general, the highest degree of confusion for both fine and medium resolution Nhecolândia classifications was related to issues of 1) scale of habitats in relation to spatial resolution of the imagery, and 2) variable flooding patterns.

The medium resolution classification resulted in some confusion between the Forest Woodland and Open Grass Savanna classes, with the Open Wood Savanna class. Although 100% of the Open Wood Savanna validation objects were correctly classified as such, an additional 35% of Forest Woodland and 20% of Open Grass Savanna were erroneously classified as Open Wood Savanna. Forest Woodland and Open Wood Savanna are both comprised of differing degrees of woody vegetation with no straightforward border between the two. Similarly, Open Wood Savanna and Open Grass Savanna are comprised of differing degrees of herbaceous grassy stratum. Many classes form a continuum along a biomass gradient, and when arbitrary ranges are chosen for delineating membership to each class, some confusion among adjacent classes is likely to occur (Hoekman et al.,2010). Additionally, the high spatial heterogeneity of the Nhecolândia landscape may not have been adequately captured at 50m spatial resolution.

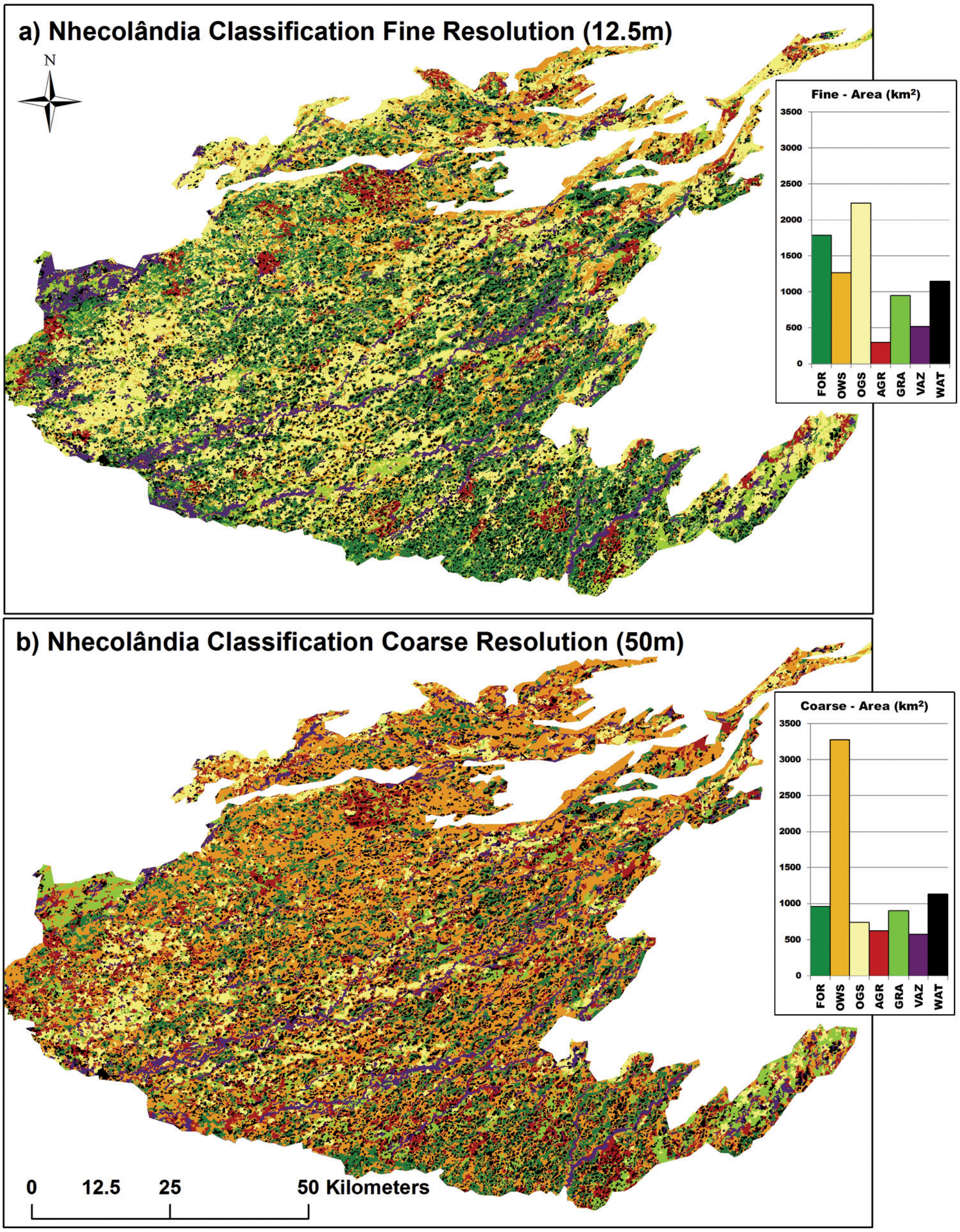

Figure 2 - a) fine and b) medium spatial resolution classification output maps of the Lower Nhecolândia subregion of the Pantanal, with a total area of (km^2) for each cover type

For example, the region contains many very small islands of forest vegetation known as *capões*, which are habitats representing islands of dense tall trees with an average minimum area of 1960 m^2 (NUNES DA CUNHA; JUNK, 2011), and would correspond to 13 pixels at 12.5 m resolution and 1 pixel at 50 m resolution imagery. Also, the *cordilheiras* units, characterized by an average of 100 m width and colonized by tall dense trees (NUNES DA CUNHA; JUNK, 2011), would correspond to 8 pixels at 12.5 m resolution and 2 pixels at 50 m resolution imagery. The small number of pixels representing these habitats in 50 m spatial resolution imagery would not allow for proper classification; the mix of grassy patches and/or forest islands together in one image object would have been classified as Open Wood Savanna instead of Forest Woodland. In comparison, for the fine spatial resolution classification, only 10% of Forest Woodland, and 5% of Open Grass Savanna validation objects were erroneously classified as Open Wood Savanna, a marked improvement from the medium resolution classification. Similarly, lakes, which are numerous in Lower Nhecolândia, are generally smaller than 50,000 m^2 (COSTA; TELMER, 2007), which roughly corresponds to 320 pixels and 20 pixels for 12.5 and 50m resolution, respectively. Further, the majority of the saline lakes have an average area of 5 000 m^2 (MEDINA-JUNIOR; REITZLER, 2005), thus corresponding to 32 and 2 pixels at a 12.5 and 50 m resolution respectively. Again the smaller number of pixels representing each lake, especially the saline lakes, is not adequate for proper lake classification with imagery at a 50 m spatial resolution (COSTA; TELMER, 2007). As such, the classification of a water class (lakes) at 50 m resolution was deliberately avoided; instead the classified lake mask from the 12.5 m resolution product was imported.

The difference in classification results among these three classes was apparent when comparing the final area (km^2) between the medium and fine spatial resolution maps. For the fine resolution classification, Nhecolândia had the highest overall contribution from the Open Grass Savanna Class (2230 km^2, 27%), followed by Forest Woodland (1790 km^2, 22%), and Open Wood Savanna (1270 km^2, 15%). However, the results for the medium resolution classification were dramatically different, with Open Wood Savanna showing an increase in total land coverage (3275 km^2, 40%), and a decrease in total land coverage for the Forest Woodland (961 km^2, 12%) and Open Grass Savanna (740 km^2, 9%) classes. This further supports the conclusion that the fine resolution imagery is the key to separating discrete habitats given the high spatial heterogeneity of this landscape.

The second major source of confusion was related to uncertainty in flooding conditions at the time of imagery acquisition. In this respect, the medium resolution classification showed the greatest degree of confusion with the *Vazante* class, where 7% of image objects were misclassified as Swampy Grassland, and 20% as Agriculture. Furthermore, 20% of Agriculture validation objects were misclassified as Open Grass Savanna, and 20% as Swampy Grassland. In this case, the fine spatial resolution classification did not perform much better: for the Swampy Grassland class, 26% was misclassified as Open Grass Savanna, and for the Vazante class, 14% was misclassified as Swampy Grassland. There are two possible explanations for these errors. 1) although planted pasture (Agriculture) typically occurs in areas not prone to long periods of inundation, given the abundance of fresh water lakes in some of the larger agricultural plots, it is likely that at least some partial/localized flooding does occur in these areas, 2)*Vazantes* and Swampy Grassland are fundamentally the same type of cover in terms of vegetation structure and inundation patterns, and thus show similar backscattering characteristics; they are differentiated only by the geometrically defined drainage channel aspect of the *Vazantes* compared to the more amorphous shape of the Swampy Grassland, and the timing and duration of inundation. Moreover, the utilization of the water mask (created from the fine spatial resolution imagery) may have contributed additional confusion to the medium resolution classification, as these very small image objects may have broken up areas that would have been segmented into larger objects had the mask not been used. Nonetheless, the authors maintain that the use of the mask was necessary to preserve the lakes as individual entities. Regardless of these sources of error, there was no significant change in the overall area (km^2) for any of these cover types between the fine and medium spatial resolution classification maps with the exception of Agriculture, which increased from 300 km^2 to 600 km^2.

Validation results for the Pantanal as a whole at 50 m spatial resolution are shown in table 1c. Overall accuracy results by subregion from highest to lowest were as follows: PARA (95%), NABI (93%), PIQU (87%), MIRA (84%), TAQF (81%), CORI (80%), AQUI (76%), NHEC (72%), and CUIA (50%). There was no accuracy assessment for the TAQR subregion as no validation data points were available for this area. The overall combined classification accuracy of ten land cover classes for the whole Pantanal was 80%. Similar to the Nhecolândia fine and medium resolution evaluation of accuracy, the primary sources of error for the medium spatial resolution classification of the whole Pantanal resulted from 1) similarities in vegetation structure and/or inundation regime, and thus similar backscattering characteristics; 2) issues of the spatial scale of the image objects in regard to the heterogeneity of the landscape and the habitats within it and the 50 m imagery pixel spacing. Again, the greatest confusion for all classification results was found with adjacent successional classes, often with similar inundation regimes and vegetation structure: for example, Forest Woodland with Open Wood Savanna; Open Wood Savanna with Open Grass Savanna; Riparian Forest with Open Wood Savanna subject to prolonged flooding; Swampy Grassland with *Vazantes* and Open Grass Savanna. These errors were expected given the similarity of these classes in terms of vegetation structure and flooding regime, and therefore similar backscattering characteristics. In many cases these habitats are found adjacent to one another, and clear cut borders between the different cover types are not readily apparent, especially given the dynamic nature of the landscape in terms of inundation. Further, based on the analysis of the classification results at fine and medium resolutions of the Lower Nhecolândia subregion, we expected the lower accuracies for, for example, the Aquidauana (AQUI) and Cuiaba (CUIA) subregions to be related to the spatial heterogeneity of the landscape, similar to Nhecolândia. The Cuiaba subregion, located in the north, also called the Pantanal of Poconé, is characterized by a landscape with *capões* and *cordilheiras* (CUNHA, 1990), which would result in similar issues already discussed for the Nhecolândia subregion. In the Aquidauana subregion confusion was mostly because Forest areas were erroneously classified as Open Wood Savanna, probably because of a similar SAR signal at 50 m scale; Open Wood Savanna - Flooded areas were classified as Riparian forest, which again is likely due to similar backscattering signal when both classes are flooded.

The produced classification maps show a landscape dominated by the Open Wood Savanna class (OWS - 39% total coverage) followed by Swampy Grassland (SGR - 14%), Open Wood Savanna subject to prolonged flooding (OWS_F - 9%), Forest Woodland (FOR - 7%), Riparian Forest (RIP - 7%), Swampy Mixed Savanna (SMS - 7%), Agriculture (AGR - 6%), Open Grass Savanna (OGS - 6%), Water (WAT - 3%), and *Vazantes* (VAZ - 2%).In general, the assessment of the Pantanal wetland as dominated by a savanna landscape observed in the present classification is consistent with several other studies of the region (ABDON et al., 1998; GEF 2004; POTT et al., 2011). The savanna landscape includes classes of Open Wood Savanna, Open Wood Savanna - Flooded, Open Grass Savanna and Swampy Mixed Savanna. These areas are subject to different degrees of inundation, from short duration (Open Wood Savanna and Open Grass Savanna) to long duration (Open Wood Savanna Flooded and Swampy Mixed Savanna). Habitats subject to long duration flooding are mostly located along major rivers, such as Swampy Mixed Savanna along the Paraguay River, Riparian forest along the Negro, Aquidauana, and São Lourenço, and Taquari rivers, and Swampy Grassland on the west border of the Pantanal, especially in the Corixo Grande, Nabileque, Taquari Fan, Taquari River, and Aquidauana subregions. Landscapes subject to short duration flooding (Agriculture, Open Grass Savanna and Open Wood Savanna) are located primarily at the eastern border of the Pantanal, in the Taquari Fan, Piquiri/São Lourenço, and Aquidauana subregions.

The classification results for the present study were compared with maps that cover the entire Pantanal wetland produced by GEF (2004) and PROBIO (2007). A visual comparison of the present classification to the landscape classification map by GEF (2004), which was based on a 5 year mosaic of Landsat imagery, shows that the map produced by the proposed method offers a more detailed spatial distribution of habitats for the region, as well as a greater number of classes (10, compared to GEF's 5). GEF's classification results are generally in agreement with the present classes; however, no accuracy assessment was provided with the GEF classification. Comparison of the present results with the PROBIO (2007) derived map, which was based on 2002 Landsat imagery acquired from July to October (dry season), shows a fair amount of agreement. The main differences between the present classification and PROBIO are related to differences in nomenclature and to the lack of published accuracy assessment of the classification map.

Table 1 - Error matrices for a) Lower Nhecolândia subregion, fine spatial resolution (12.5 m), b) Lower Nhecolândia subregion, medium spatial resolution (50 m), c) Collective for the entire Pantanal wetland, medium spatial resolution (50 m)

(a)	CLASSIFIED AS								
	Forest Woodland	Open Wood Savanna	Open Grass Savanna	Agriculture	Swampy Grassland	Vazante	Water	Row Total	Error of Omission (%)
Forest Woodland	39	5	2	0	0	0	0	46	15
Open Wood Savanna	2	27	3	1	0	1	0	34	21
Open Grass Savanna	1	2	38	0	1	2	0	44	14
Agriculture	0	1	2	21	1	1	0	26	19
Swampy Grassland	0	0	9	0	23	2	0	34	32
Vazante	0	0	1	1	4	20	1	27	26
Water	0	0	4	0	4	0	78	86	9
Column Total	42	35	59	23	33	26	79	297	
Error of Commission (%)	7	23	36	9	30	23	1	overall accuracy	83

(b)	CLASSIFIED AS								
	Forest Woodland	Open Wood Savanna	Open Grass Savanna	Agriculture	Swampy Grassland	Vazante	Water	Row Total	Error of Omission (%)
Forest Woodland	11	6	0	0	0	0	0	17	35
Open Wood Savanna	0	9	0	0	0	0	0	9	0
Open Grass Savanna	0	2	7	0	1	0	0	10	30
Agriculture	0	0	1	3	1	0	0	5	40
Swampy Grassland	0	0	0	1	7	0	0	8	13
Vazante	0	0	0	3	1	11	0	15	27
Water	0	0	0	0	0	0	0	0	
Column Total	11	17	8	7	10	11	0	67	
Error of Commission (%)	0	47	13	57	30	0		overall accuracy	72

(c)	CLASSIFIED AS:											
	Forest Woodla nd	Riparian Forest	Open Wood Savanna	Open Wood Savanna Flood	Open Grass Savanna	Swampy Grassland	Swampy Mixed Savanna	Agriculture	Vazante	Water	Row Total	Error of Omission (%)
Forest Woodland	60	4	14	5	0	0	0	0	0	0	83	28
Riparian Forest	4	23	0	3	0	0	1	0	0	0	31	26
Open Wood Savanna	1	0	66	0	0	1	0	0	0	0	68	3
Open Wood Savanna Flood	0	4	5	31	0	0	0	1	0	0	41	24
Open Grass Savanna	0	0	3	0	17	0	0	3	0	0	23	26
Swampy Grassland	0	0	1	0	4	51	0	3	2	1	62	18
Swampy Mixed Savanna	0	1	0	3	0	1	4	0	0	0	9	56
Agriculture	0	0	0	0	3	2	0	22	0	0	27	19
Vazante	0	0	0	0	1	6	0	1	23	0	31	26
Water	0	0	0	0	0	0	0	0	0	14	14	0
Column Total	65	32	89	42	25	61	5	30	25	15	389	
Error of Commission (%)	8	28	26	26	32	16	20	27	8	6	overall accuracy	80

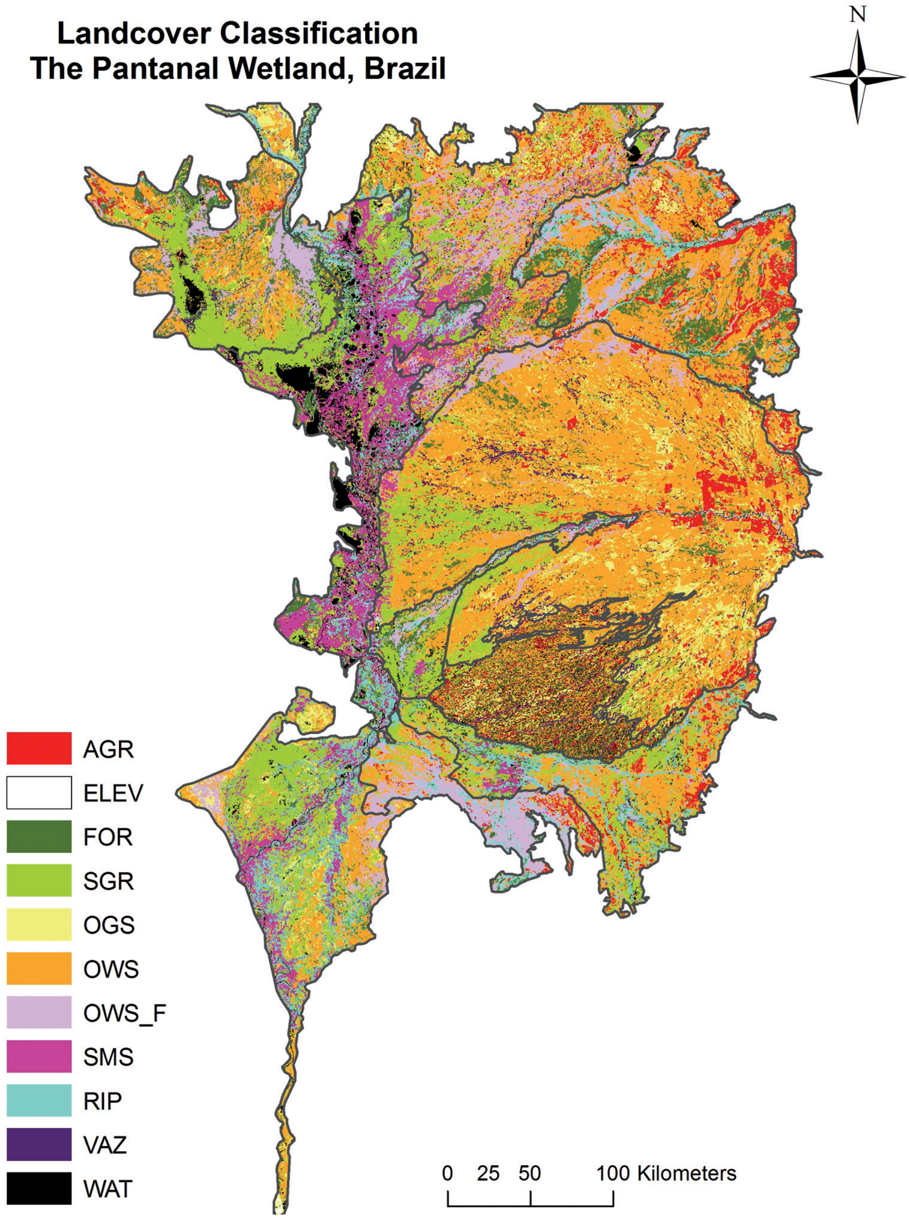

Figure 3 - Habitat classification for the Pantanal. AGR (agriculture), ELEV (Elevated areas not subject to inundation), FOR (Forest), SGR (Swampy grassland), OGS (Open grass savanna), OWS (Open woody savanna), OWS_F (Open woody savanna – flooded), SMS (Swampy mixed savannah), RIP (Riparian forest), VAZ (Vazante), Water (Open water not covered by vegetation canopies)

CONCLUSION

Conservation and management of the wildlife habitats of the Pantanal require careful consideration of the implications of both changes to natural inundation patterns, and alterations of key land cover, as a result of anthropogenic activity. It is therefore imperative to have an accurate, detailed classification of the spatial distribution of habitats in this region to better understand species use of the habitats, migration corridors and consequences of habitat change as a result of natural and anthropogenic disturbances, so that sustainable management practices and effective conservation units can be established.

This research evaluated (1) the classification products generated with L and C-band, dual season fine and relatively medium spatial resolution imagery for the Lower Nhecolândia subregion of the Pantanal, and (2) the classification product generated for the whole Pantanal using medium resolution L and C-bands, dual season imagery. Specifically, for the Nhecolândia subregion, which is characterized by a mosaic of small scale units, such as *capões*, *cordilheiras*, and lakes on a background of forest and grassland, classifications produced using the same methods, show a considerable improvement in accuracy with the fine spatial resolution imagery (83% vs.72% for fine and medium resolution, respectively).This difference was likely a result of the constrains of the 50 m resolution imagery to properly characterize the radar signal of small habitats such as, for example, *capões*, *cordilheiras*, which at this resolution are represented by 1 or 2 pixels.

The results of the 50 m spatial resolution classification for the entire Pantanal provide a detailed classification land cover map showing the spatial distribution of aquatic, terrestrial and transitional habitats for the entire ecosystem based on a combination of L-band dual polarization/dual season and C-band dual polarization/dry season SAR satellite imagery with overall accuracy of 80%. Although well within the acceptable accuracy range for similar large scale wetland classifications, the authors conclude that significant improvements could be achieved in other subregions of the Pantanal by utilizing a fine spatial resolution imagery dataset similar to that used for the Lower Nhecolândia subregion; in particular, the subregions with a high heterogeneity of landscape, such as the Cuiaba subregion (overall accuracy of only 50%). In addition, the authors surmise that further improvements in accuracy could be gained by the addition of both L and C-band data acquired at several temporal stages throughout the entire hydrological cycle rather than just at a single wet and single dry period.

This research has provided a detailed fine resolution land cover map of the Lower Nhecolândia subregion and a relatively medium resolution land cover map of the whole Pantanal. Final remarks are focused on the issue of desired scale. Spatially, a relationship among desired numbers of classes, spatial resolution of the remotely sensed imagery, separability of the backscattering signal, size of the minimum areas of interest, and extent of the study area must be considered. In landscapes highly heterogeneous in nature such as the Pantanal, detailed classification with the goal of spatial habitat information for determining refuge zones for terrestrial species, connectivity of aquatic habitats, resource allocation, species distribution as a result of the flood-pulse, and risks of environmental changes, must be conducted at a finer spatial resolution, or the subsequent classification could overlook significant features of the landscape.

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