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Large-scale habitat mapping of the Brazilian Pantanal wetland: A synthetic aperture radar approach

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ABSTRACT

This study uses 50 m spatial resolution, dual-season, HH and HV L-band ALOS/PALSAR, and HH and HV C-band RADARSAT-2 data, as well as a comprehensive set of ground reference points, to map the diverse habitats of the hydrologically variant subregions of the Pantanal by using a hierarchical object based image analysis approach. First, mean and standard deviation values of image object training sites were evaluated, and used as the basis for forming preliminary land cover class thresholds for each subregion. Then, a combination of additional refined thresholds, hierarchical rules, and a supervised nearest neighbor algorithm (eCognition Feature Space Optimization) employing several features as primary inputs (mean, standard deviation, seasonal change detection, brightness, maximum difference, area, roundness, brightness, compactness, shape index, and length/width) was utilized, resulting in the definition and classification of ten habitat classes: Forest/Woodland, Riparian Forest, Open Wood Savanna, Open Wood Savanna subject to prolonged flooding, Open Grass Savanna, Agriculture, Swampy Grassland, Swampy Mixed Savanna, *Vazantes*, and Water. This classification was achieved with an overall accuracy of 80% for the entire Pantanal. The produced habitat spatial distribution maps will provide vital information for determining refuge zones for terrestrial species, and connectivity of aquatic habitats during the dry season, as well as providing crucial baseline data to aid in monitoring changes in the region, and to help define conservation strategies for habitat in this wetland.

1. Introduction

Wetlands throughout the world are recognized as biodiversity hotspots (Mitsch & Gosselink, 2007), particularly large and environmentally heterogeneous systems that support a variety of habitats with a multitude of feeding and reproductive niches (Alho, 2008). One such heterogeneous wetland ecosystem, the Pantanal wetland of South America, is made up of a complex of seasonally inundated floodplains, and is considered a category of temporary wetlands subject to a spatially and temporally variable monomodal flood pulse (Junk, Bayley, & Sparks, 1989). Such seasonally inundated floodplain ecosystems are characterized as being periodically flooded through lateral overflow of the main course of the river(s), as well as through rainfall and run-off channels, resulting in a seasonally dynamic mosaic of aquatic, semi-aquatic, and terrestrial habitats (Junk et al., 1989). The ecotone between aquatic and terrestrial zones shifts location seasonally over the inundation cycle. This variability, combined with local topography, is a key driver of the ecological complexity found in aquatic, semi-aquatic and terrestrial vegetation patterns (Hamilton, 2002), and thus contributes to a high degree of habitat diversity within the Pantanal expressed by a unique landscape distinguished by different compositions of savanna vegetation, abundant species of aquatic vegetation, and different types of floodplain forests (Abdon, da Silva, Pott, Pott, & Da Silva, 1998; Nunes da Cunha & Junk, 2011; Pott & Pott, 2000). In addition to the floristic diversity, a large number of hydrochemically varied lakes, waterways, and other fluvial geomorphological patterns are observed, generating a complex mosaic of wetland habitats (Costa & Telmer, 2006; Mariot et al., 2007; Nogueira et al., 2011; Por, 1995). This diversity of habitats supports a vast array of flora and fauna (Alho, Camargo, & Fischer, 2011); as such, the Pantanal wetland was recognized as a "National Heritage" site in the 1988 Constitution of Brazil, and as a Wetland of International Importance in the Ramsar Convention. Although still considered a relatively pristine wetland (Junk et al., 2006), the Pantanal is currently under threat as a result of habitat loss and habitat degradation caused primarily by agricultural pressures occurring both on the surrounding plateau and, increasingly, within the floodplain itself (Alho, Mamede, Bitencourt, & Benites, 2011; Godoy et al., 2002; Harris et al., 2005; Junk et al., 2006; Seidl, 2000).

The change or destruction of landscapes within this spatially complex wetland habitat system can cause the disturbance of key biological processes controlling abundance and interactions of faunal species (Mitchell, 2005; Tews et al., 2004). Furthermore, knowledge regarding the spatial distribution of ecologically significant wildlife habitat is

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vital in terms of forming baseline data for identifying habitat protection zones, implementing future change detection studies and supporting applications relating to resource management, habitat reconstruction, and recovery of species at risk (Mitchell, 2005; Tews et al., 2004). Therefore, developing efficient techniques for mapping wetland landscape habitats is of critical importance for implementing appropriate conservation strategies.

Classic methods for mapping wetland vegetation habitats have been largely based on ground surveys of soil and vegetation inventories gathered through extensive and time consuming field work requiring ancillary data analysis and visual estimations of ground cover. As a consequence, such methods are only practical on small scales, and do not provide spatially continuous information over large regions (Hewes, 1951; Lee & Lunetta, 1996; Mitsch & Gosselink, 2007). In many cases, remote sensing technology, combined with ground truth data, offers the most economical and reliable process for determining ecologically valuable information regarding the characteristics of habitats, and monitoring environmental changes resulting from anthropogenic or natural processes, across multiple scales (Kerr & Ostrovsky, 2003). Furthermore, synthetic aperture radar (SAR) imagery has been successfully used for mapping inundation, land-cover, and biophysical properties in regions of dense vegetation or with frequent cloud cover (Costa, 2004; Hess, Melack, Barbosa, & Gastil, 2003; Rebelo, 2010; Silva, Costa, & Melack, 2010).

Specifically in the Pantanal, various remote sensing methods have been used to map features of the landscape, but the resulting classification maps have been restricted to: 1) a single habitat, such as lakes in the Nhecolândia subregion (Costa & Telmer, 2006; Novack, Hayakawa, Bertani, & Zani, 2010); 2) a single subregion or a small subset at a local scale (Abdon et al., 1998; Arieira et al., 2011; Evans & Costa, 2013; Galvão et al., 2003; Novack et al., 2010); or 3) a large scale classification of the entire Pantanal at a either a coarse spatial resolution (Evans, Costa, Telmer, & Silva, 2010), or using imagery over a time span of approximately five years (GEF, 2004; PROBIO, 2007).

The objective of this research is to address some of the limitations encountered in the above-mentioned publications by defining on a regional scale the wetland habitats of each of the hydrological subregions of the Pantanal, thus producing a final product covering the entire Pantanal, using a finer spatial resolution SAR imagery set (50 m) acquired during one hydrological cycle, a comprehensive set of ground reference data, and employing a hierarchical object based image analysis (OBIA) approach.

2. Study area

The Pantanal wetlands are located in the center of South America, primarily in Brazil, with roughly 10% reaching into Bolivia, and Paraguay (Fig. 1). This wetland ecosystem is one of the largest and most important tropical wetlands globally, with estimates suggesting that the inundated area covers approximately 160,000 km^2 during maximum flooding. The Pantanal floodplain is bordered by an upland drainage basin of elevated plateaus and low mountains to the north and east, and heavily eroded ancient volcanic mountains to the west (Heckman, 1998; Por, 1995), with the entire Pantanal watershed occupying an area of approximately 362,000 km^2 (Junk et al., 2006). The Pantanal floodplain is situated in a large depression of post-Cretaceous origin (Junk, Nunes da Cunha, da Silva, & Wantzen, 2011), and is a sedimentary basin composed of a mosaic of alluvial fans of Pleistocene origin (Alho, 2008). The altitude in the floodplain varies from roughly 80 to 150 m asl and the topographical gradients are negligible, with the slope ranging from 0.3 to 0.5 m/km east–west and 0.03 to 0.15 m/km north–south (Mamede & Alho, 2006).

The climate of the Pantanal is tropical, semi-humid to humid, with seasonally intense rainfall and a marked dry season. Average annual precipitation is approximately 1400 mm, with 70–80% occurring in the rainy season from October to April (GEF, 2004).

The Pantanal is a rich hydrological complex formed by several major tributaries of the Paraguay River. The low topographical variation of the floodplain results in a slow release of water from the upland drainage basin, through the floodplain via these tributaries to the Paraguay River running north–south along the western border (Hamilton, 2002). The riverbeds of the main tributaries are fairly well-delineated at their upper reaches, but become less defined as they approach the Paraguay River as a result of the low topographical gradient of the floodplain. Consequently, river discharge volume often decreases downstream rather than increasing, as is the norm (Por, 1995). Expansive areas are covered by water during annual flooding that extends from January to July. The drainage network and the rainfall patterns of the Pantanal support an annual monomodal flood regime that varies both temporally and spatially (Fig. 1), thus delineating several sub-regions with diverse characteristics in terms of ecology, hydrology and geomorphology. Flooding in these subregions is distinctly seasonal, but the timing, amplitude and duration of inundation vary considerably as a result of both the delayed release of floodwaters and regional rainfall patterns (Table 1). Maximum inundation can occur as early as January in the north and east, and as late as July in the south (4–5 months after peak rainfall). A lag time of 1–2 months typically occurs between peak river channel discharge and maximum inundation depth/extent of the surrounding plain (Girard, 2011; Hamilton, Sippel, & Melack, 1996). Hamilton et al. (1996) delineated ten Pantanal subregions based on geological and hydrological differences: 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) (Fig. 2). In general, the duration and intensity of the inundation regime increase from east to west, and from north to south: the lowest amplitude, short duration flooding occurs in the eastern PIQU, TAQF, NHEC and AQUI subregions, while the highest amplitude, long duration flooding occurs adjacent to major river systems, particularly along the Paraguay River in the CORI, PARA and NABI subregions (GEF, 2004; Hamilton et al., 1996). Typically, the seasonal inundation patterns in the northern subregions are fairly regular; however, the MIRA, NHEC and AQUI subregions in the south show some short-term variability, and often lack a discrete seasonal flood peak, and the NABI region in the south can be highly variable in flood extent among years (Hamilton et al., 1996) (Table 1). This highly variable and dynamic flooding regime, and the connections and disconnections established between different elements of the landscape via the seasonal floodpulse, are the most important ecological phenomena in the Pantanal, and the key drivers behind the high habitat diversity of the wetland (Junk et al., 1989, 2006; Mamede & Alho, 2006).

As a geologically young landscape, endemism is rare in the Pantanal; rather, the flora of the wetland is heavily influenced by the main neighboring phytogeographic domains. The Pantanal is primarily a savanna (*cerrado*) landscape, borrowing from the *cerrado* biome to the east; however, the Paraguay floodplains are also influenced by the Amazon forest biome, and a strong Chaco biome influence can be seen in the Nabileque and Miranda subregions (Pott, Oliveira, Damasceno-Junior, & Silva, 2011). At a broad scale, the landscape units in the Pantanal wetland are characterized by 1) forest; 2) savanna; and, 3) frequently and/or permanently aquatic or swampy terrain, although there is not always a definitive boundary between these three landscapes, and some classes of forest and savanna also periodically flood. The phytogeographic units of the Pantanal can be defined in terms of geomorphology (inundation regime/elevation) (Nunes da Cunha, Junk, & Leitao-Filho, 2007), vegetation structure (Pott et al., 2011), or a combination of both (Nunes da Cunha & Junk, 2011). There are five main geomorphologic subunits that categorize the landscape of the Pantanal as described in Nunes da Cunha et al. (2007): 1) elevations that reach 1–2 m above mean flood level, and thus are rarely or never subject to inundation; 2) periodically flooded flat plains; 3) shallow natural drainage channels; 4) depressions that remain swampy, even in dry months;