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REVIEW ARTICLE

Remote sensing of wetlands in South America: status and challenges

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ABSTRACT
South America has a large proportion of wetlands compared with other continents. While most of these wetlands were conserved in a relatively good condition until a few decades ago, pressures brought about by land use and climate change have threaten their integrity in recent years. The aim of this article is to provide a bibliometric analysis of the available scientific literature relating to the remote sensing of wetlands in South America. From 1960 to 2015, 153 articles were published in 63 different journals, with the number of articles published per year increasing progressively since 1990. This rise is also paralleled by an increase in the contribution of local authors. The most intensively studied regions are the wetland macrosystems of South American mega-rivers: the Amazon and Paraná Rivers, along with the Pantanal at the headwaters of Paraguay River. Few studies spanned more than two countries. The most frequent objectives were mapping, covering all types of wetlands with optical data, and hydrology, focusing on floodplain wetlands with microwave data as the preferred data source. The last decade substantial growth reflects an increase in technological and scientific capacities. Nevertheless, the state of the art regarding the remote sensing of wetlands in South America remains enigmatic. Fundamental questions and guidelines which may contribute to the understanding of the functioning of these ecosystems are yet to be fully defined and there is considerable dispersion in the use of data and remote-sensing approaches.

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1. Introduction

According to the Ramsar Convention on Wetlands, ‘wetlands are areas of marsh, fen, peatland, or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish, or salt, including areas of marine water the depth of

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Supplemental data for this article can be accessed here.

which at low tide does not exceed six meters.’ Further it explains that, ‘wetlands may incorporate riparian and coastal zones adjacent to the wetlands, and islands or bodies of marine water deeper than six meters at low tide lying within the wetlands’ (Ramsar 1971). Other definitions emphasize the presence of diagnostic features such as the presence of water table saturating or inundating the substrate, which promotes an anoxic environment, plants adapted for life in saturated soil conditions and/or hydric soils (Mitsch and Gosselink 2007).

South America is the continent with the largest area covered by wetlands (>3×10^6 km^2), representing more than 20% of its surface (Zhu and Gong 2014), well above the 6.2–7.6% estimated for the surface of the globe (Lehner and Döll 2004; Junk et al. 2013). In addition, the environmental heterogeneity of the continent generates a great variety of wetland types (Kandus, Minotti, and Malvárez 2008; Benzaquén et al. 2013; Junk et al. 2014). Main drivers for this diversity are the latitudinal and longitudinal extent of the continent, the altitudinal range from sea level to 6962 m.a.s.l., and its geological and climatic diversity, with the influence of both the Pacific and Atlantic Oceans (Veblen, Young, and Orme 2007; Junk 2013). The abundance of wetlands associated with floodplains of large rivers such as the Amazon, the Orinoco, and the Paraguay-Paraná has led to South America being named ‘the fluvial continent’ (McClain 2002; Neiff and Malvárez 2004). There are also a myriad of inland wetlands fed by groundwater, local rainfall and melting snow, and thousands of kilometres of coastal wetlands (Junk et al. 2014).

Wetlands play a key role in hydrological and biogeochemical cycles, harbouring a large part of the world’s biodiversity, and provide multiple services to humankind (Millennium Ecosystem Assessment 2005). However, according to the Scientific and Technical Review Panel of the Ramsar Convention, during the twentieth century, the global extent of wetlands has declined by 64% to 71%. Furthermore, wetland losses and degradation continue across the globe due to pressures in the form of land reclamation, hydrological changes, intense resource exploitation, and pollution (Gardner et al. 2015). Although most wetlands in South America have been considered in relatively good condition until a few decades ago (Brinson and Malvárez 2002), in recent years their integrity has been threatened by land-use pressures, mainly agriculture and livestock grazing, and climate change. Despite the importance of wetlands, South American countries still do not have inventories with detailed information on their areal extent, conservation status, or wetland type, nor are there wetland monitoring plans envisaged for the medium or long term. Nevertheless, it is worth mentioning the recent progress regarding the wetland inventory of Colombia, which has benefited from advances in conceptual approaches and the use of remote-sensing data in order to identify and delimit wetlands (Estupinan-Suarez et al. 2015).

For South American countries, it is critical to have systematic and consistent measurements of biogeophysical variables on wetlands, and remote sensing is a key tool to address this issue. The use of remote sensing to improve wetland ecosystem knowledge, monitoring, and inventory has always been attractive as it overcomes the main difficulty of coverage and accessibility. Remote sensing is less expensive than research based solely on fieldwork and provides information over a broader range of spatial and temporal scales (Brisco et al. 2011; Gallant 2015). However, remote sensing of South American wetlands remains a challenge.

The classic paradigm envisages wetlands as transitional between terrestrial and aquatic ecosystems, whereas we consider wetlands as proper ecosystems, which are structurally and functionally different from their terrestrial and aquatic counterparts. Although in some cases, they might represent transitions, such as wet meadows along coastal zones, most have their own identity, such as peat bogs. This fact causes great differences in how wetlands are studied and places them in an equivalent level to other ecosystems. Contrary to forests and grassland ecosystems, wetlands are not associated with a unique physiognomy. For example, riparian forests, swamps, scrublands, marshes, savannas, grasslands, peat bogs, wet meadows, extended aquatic prairies, lagoons and shallow lakes with open water, and even fields with bare wet soil are all wetlands (Mitsch and Gosselink 2007). They can be tiny patches in the landscape or they can occupy large areas, assembled into complex macrosystems which dominate the landscape with mosaics of different wetland types along with other environments. The main diagnostic feature of wetlands is their functionality in terms of hydrogeomorphic regime (i.e. hydroperiod), which can help us understand how wetlands develop and behave (Vaughan et al. 2009). The hydrology (both surface and groundwater) is also one of the main drivers, which constrains remote-sensing approaches and strategies (Gallant 2015). Time series of images are required to address the complexity of these ecosystems and to establish their boundaries.

A large spectrum of remote-sensing data are available with sensors providing valuable physical data of the Earth, boarded on satellites, airborne missions, and unmanned aerial vehicles. Guo et al. (2017) provided an overview of the main types of sensors used, the topics covered, and the methods developed for wetland research across the globe. The selection of remote-sensing data type depends on the main objective of the study, the structural and functional characteristics of the wetland, and the data availability: from single scenes with high spatial resolution to time series with low to medium spatial resolution; from optical to microwave data; and from active to passive sensors. Furthermore, multisensor approaches can be used and should be coupled with fieldwork and expert knowledge of the study area.

The aim of this article is to provide a bibliometric analysis which investigates the available scientific literature related to remote sensing of wetlands in South America, by addressing the following questions:

- What are the trends in scientific article production in South America, as a whole and by country?
- What is participation of authors from South American countries, and how has this changed through time?
- Which wetlands have been studied using remote sensing and what were the main objectives of these studies?
- Which combinations of remote-sensing systems and sensors are used to address different objectives for different types of wetlands?
- Do these articles highlight priority research themes related to wetland management needs?

We discuss the bibliometric results in terms of the main research themes for remote sensing of wetlands, particularly in relation to their environmental management needs.

2. Methods

The bibliometric analysis sought to identify fundamental trends from 1960 to 2015 using Scopus (Elsevier 2016). This indexing database lists peer-reviewed titles and provides an easily navigable interface that facilitates the interrogation of scientific articles, authorships, affiliations, and citations (Sullo 2007). The analysis started with keyword-based searches of major peer-reviewed journal titles related to Life and Physical Sciences. Sets of keywords associated with three main component arguments were combined (Table 1): the ecosystem ('wetland' and 14 other related terms), the technology ('remote sensing' and eight other related terms), and the geographical area ('South America' and 13 specific countries). All possible keyword combinations were used to search Scopus. The searches were case insensitive and included plural and singular terms (e.g. 'wetland*'). Outputs were manually filtered to avoid duplication and to identify application-related articles.

We also addressed the number of wetland remote-sensing publications with studies of other types of ecosystem by replacing the ecosystem term 'wetland' with 'grassland' or 'forest' in the keyword formula 'ecosystem + remote sensing + geographic area.' To scale the results globally, a similar series of searches were conducted in which the geographical region argument was omitted. Along with the bibliometric information extracted from Scopus, the following fields were registered for each publication: the main scope of journal, the country of publication, the country in which the study was conducted, the wetland ecosystem, the affiliations of the authors, the platform-sensor/s used, the type of sensor, and the main objective of the work.

3. Results

The Scopus database incorporates 153 articles from 63 different journals related to the remote sensing of wetlands in South America from 1960 to 2015. A complete list of these articles is available as Figshare. Despite the extensive use of local names for the type of wetland (Table 1), combining the search terms 'marsh,' 'swamp,' or 'floodplain' together with the name of each country identified the bulk of the published articles. This

Table 1. Keywords used grouped in three main thematic areas.

Ecosystem	Technology	Geographic area
wetland	Remote sensing	South America
swamp	Moderate Resolution Imaging Spectroradiometer (MODIS)	Argentina
marsh*	Landsat	Bolivia
floodplain	Multispectral	Brazil
shallow lake*	Synthetic aperture radar (SAR)	Colombia
lake*	Radar	Chile
lagoon*	Gravity Recovery and Climate Experiment (GRACE)	Ecuador
mangrove*	Light detection and ranging (lidar)	French Guiana
peatbog	Microwave	Guyana
peatland		Paraguay
vernal pool[a]		Perú
mires[a]		Surinam
wet prairie[a]		Uruguay
tidal flats[a]		Venezuela
moores[a]		

The search included plural and singular terms (e.g. 'wetland*') and was case insentitive.
[a]No results were found for the term.

figure is reduced to just 38 articles when using only the combined keywords 'wetland* + remote sensing' for South America. When terms such as marsh, swamp, and floodplain were added as keywords, the number of articles returned by the Scopus database increased by about four times.

Similar number of articles were obtained for grassland ecosystems (36), while forest generated seven times more articles (265). Interestingly, similar proportions were found at the global scale, with 1634 articles relating to the remote sensing of wetlands, 1601 articles relating to the remote sensing of grasslands, and 8215 articles relating to the remote sensing of forests.

The number of articles published per year has increased since 1990 (Figure 1), with only a single article published before 1990. By 2001, the annual percentage of increase reached 47%, stabilizing around 20% afterwards. Brazil has been publishing systematically since 1989, while Argentina began to publish a decade later. Contributions from other countries were rather sporadic.

A total of 439 local authors have participated in the South American remote-sensing studies gathered by Scopus. Their contribution showed an increasing trend, starting with a ratio of local to foreign authors of 0.33 during the 1990s, and staying around 0.7 for the last 10 years (Figure 2). Considering individual countries, local author contribution for Brazil was very variable with an average of 0.55, while in the case of Argentina and Venezuela, the ratio was 0.86 and 0.71, respectively. This ratio for Peru and Bolivia was around 0.25, and a similar figure was obtained for articles addressing multiple countries or regional goals.

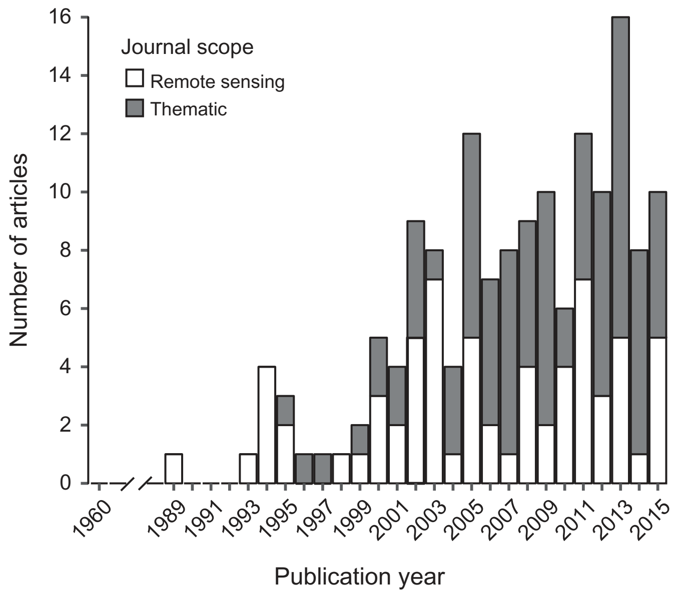

Figure 1. Number of peer-reviewed articles published per year, which focus on the remote sensing of wetlands in South America. Journals with a remote-sensing scope are those that publish results on the theory, science, application, and technology of remote sensing, while journals with a thematic scope are those focused on specific disciplines (e.g. ecology, geomorphology, and hydrology).

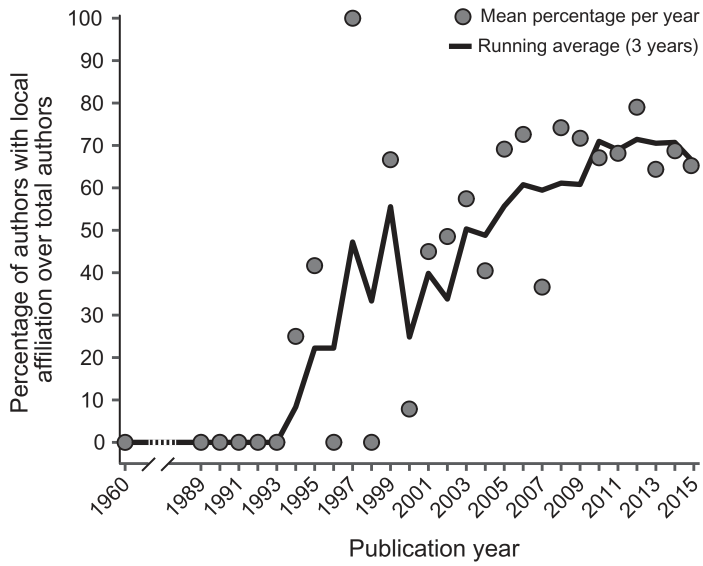

Figure 2. Participation of local authors. The line indicates the running average of ratio local to total number of authors per year. Dots show the mean percentage of local authors per year.

Regarding the scope of the journals, less than half of articles were published in journals specializing in remote sensing (43.8% in 12 different journals), while the remainder were published in thematic journals (56.2% in 51 different journals). International scientific publishers were the dominant choice except for nine journals from Brazil (Table 2).

Most of the published articles focused on wetlands in Brazil (57.5%) and Argentina (23.5%), followed by Peru (4.6%) and Venezuela (3.3%). Only 5.2% of the published articles incorporated two or more countries (Figure 3). With regard to wetland types, nearly 60% of articles examined the wetland macrosystems of South American mega-rivers: the Amazon River floodplain (58 articles), the Paraná River floodplain (18 articles), and

Table 2. Sensor types and satellite or airborne systems used in the reviewed publications.

Sensor type	System
Optical	**Landsat Thematic Mapper (TM), Enhanced Thematic Mapper (ETM)**, and **Operational Land Imager (OLI): 71.4%; Aqua/Terra Moderate Resolution Imaging Spectroradiometer (MODIS): 11.7%**; IKONOS: 3.9%; National Oceanic and Atmospheric Administration satellite/Advanced Very High Resolution Radiometer (NOAA/AVHRR): 3.9%; Airborne hyperspectral: 2.6%; light detection and ranging (lidar): 1.3%; China-Brazil Earth Resources Satellite (CBERS): 1.3%; Multisensor: 3.9%
Active microwave: synthetic aperture radar	**Multisensor: 34.7%; Japanese Earth Resources Satellite (JERS): 20.4%; Envisat/Advanced synthetic aperture radar (Envisat/ASAR): 12.2%**; Airborne: 8.2%; Advanced Land Observing Satellite/Phased Array L-band synthetic aperture radar (ALOS/PALSAR): 8.2%; Spaceborne Imaging Radar-C/X-band synthetic aperture radar (SIR-C/X-SAR): 6.1%; Radarsat: 6.1%; European Remote-Sensing Satellite (ERS): 4.1%
Optical and active microwave SAR	**Multisensor: 100%**
Passive microwave	**Nimbus-7: 60%; Multisensor: 40%**
Thermal	**Multisensor: 100%**
Gravimetry	**Gravity Recovery And Climate Experiment (GRACE):100%**

The percentage of the sensor type is indicated for each system; systems in bold letter account for more than 10% of the studies on a given sensor type.

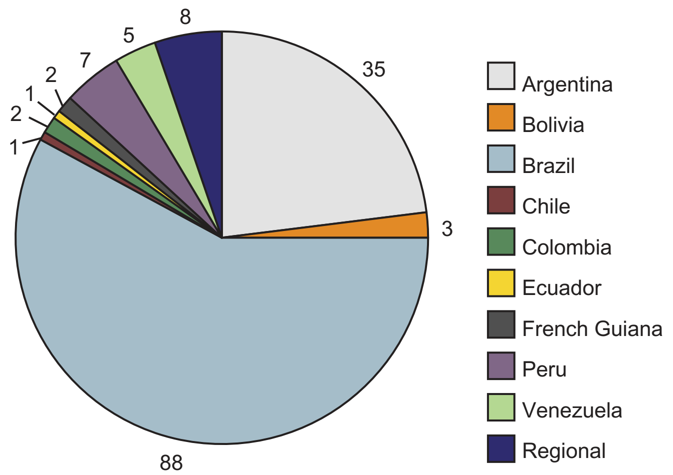

Figure 3. Number of publications per country. The number of studies per country is shown beside the pie chart ('regional' reflects studies involving more than one country). No records were found for Surinam and Guyana. See the electronic version for the colour version.

Pantanal at the Upper Paraguay Basin (14 articles) (Figure 4). A small subset was related to floodplains of other large rivers with smaller basins, such as the San Juan and Apure rivers in Venezuela and the Araguaia and San Francisco in Brazil, along with some regional comparisons. Studies of South American coastal wetlands included 17 articles on coastal marshes and lagoons and 12 articles on mangrove swamps, while shallow lakes were the special focus of 11 articles. Wetlands of the Puna and High Andes regions, both peatbogs and shallow lakes, were the focus of six articles. The remaining nine articles corresponded to a variety of wetlands including marshes, veredas (palm swamps), and reservoirs.

Mapping was the most frequent objective with a total of 55 articles, incorporating all wetland types (Figure 5(a)) and using optical data as preferred source of information

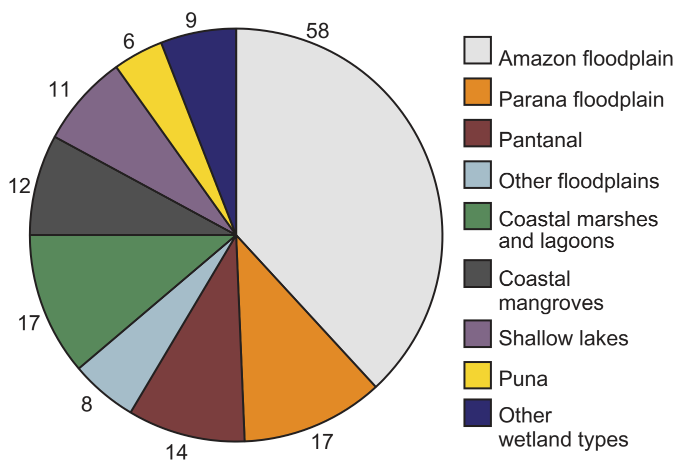

Figure 4. Number of publications per wetland type. The number is shown beside the pie chart. See the electronic version for the colour version.

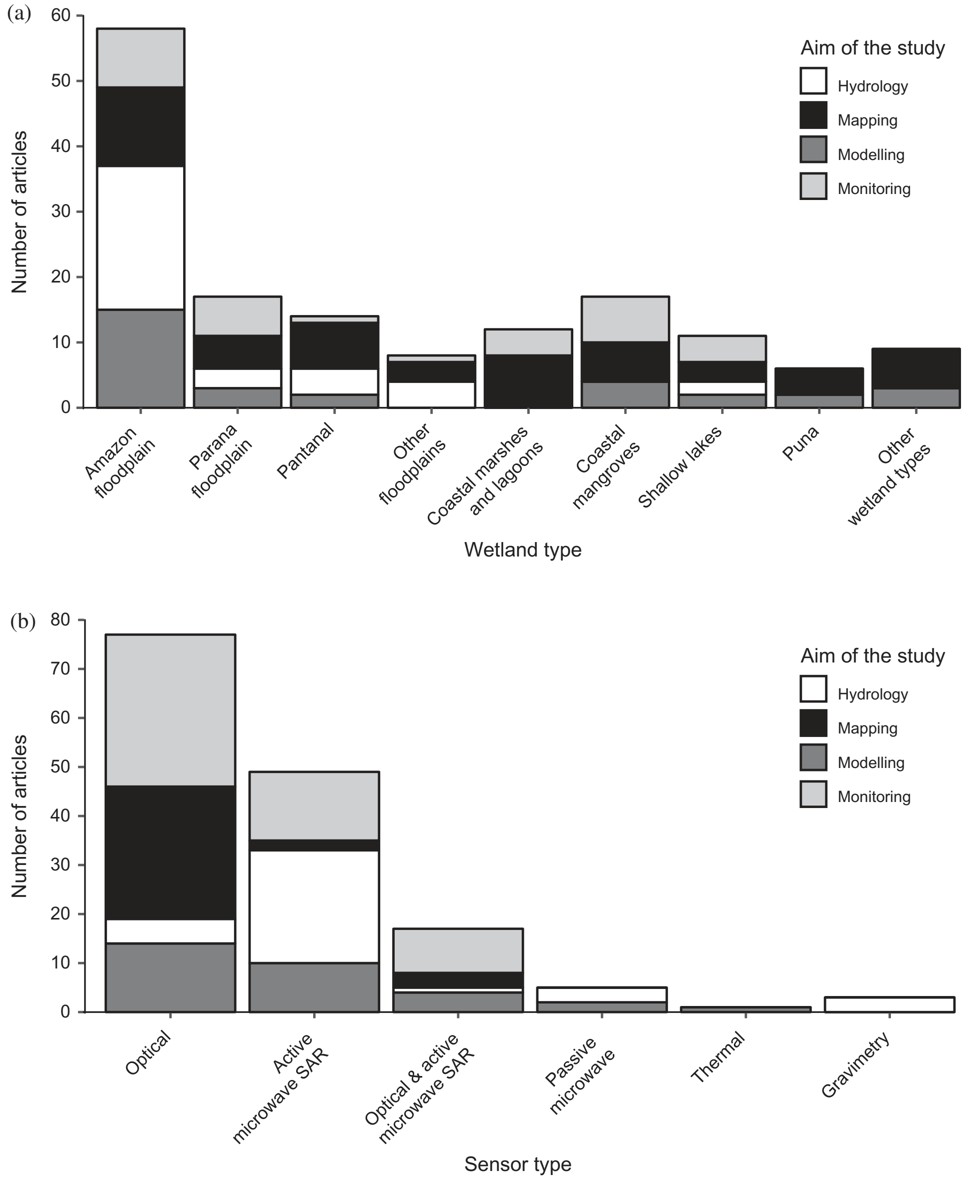

Figure 5. Main objectives of the peer-reviewed articles: (a) according to the studied wetland type; (b) according to the sensor type.

(58.2%) (Figure 5(b)). Wetland hydrology was the second most frequent research objective with a total of 35 articles focused on floodplain wetlands and using microwave data as preferred source of information (77.1%). The monitoring of biophysical parameters and land-cover changes was assessed in 32 articles, addressing the environmental variability of large floodplains and coastal wetlands with optical data (84.4%). Modelling of biophysical parameters was reflected in 31 publications, incorporating most wetland types, with both optical and microwave data. Mapping articles were mainly focused on wetland identification and delineation. Most articles addressed the Amazon Basin (i.e. Saatchi et al. 2000; Hess et al. 2002; Souza-Filho 2005; De-Campos et al. 2013; De Furtado et al. 2015). Other preferred wetlands were the Brazilian savanna (Barbosa and Maillard 2010), the Pantanal in the upper Paraguay (Evans and Costa 2013), the Argentinian Pampas (Guerschman et al. 2003), and the High Andes and Puna (Boyle, Caziani, and Waltermire 2005; Izquierdo, Foguet, and Ricardo Grau 2015).

Mapping articles also addressed the discrimination of wetland types (i.e. Mertes et al. 1995; Kandus, Karszenbaum, and Frulla 1999; Salvia et al. 2009; Evans et al. 2014), the functioning of floodplain wetlands (Marchetti et al. 2016), and the identification of vegetation types (i.e. Long and Hardin 1994; Isacch et al. 2006; Silva et al. 2008; Arieira et al. 2011; Marchetti et al. 2013). Some studies highlighted the use of synthetic aperture radar (SAR) data particularly for the discrimination of herbaceous plant types (Costa 2004; Costa and Telmer 2006; Silva et al. 2008; Sartori et al. 2011) since signal saturation usually occurs in optical data for herbaceous cover with high biomass. Moreover, the combination of plant geometry with the presence of the water table saturating or above the substrate produce different signal–target interaction mechanisms which facilitate the discrimination of wetland types using SAR. Various contributions addressed mapping aquatic vegetation in the Amazon floodplain based on multi-temporal, multi-frequency, and multi-polarization approaches (i.e. Costa et al. 2002; Hess et al. 2003; Silva, Costa, and Melack 2010). It is also worth highlighting the mapping efforts focused on shallow lakes within extensive regional wetlands using SAR data in the Pantanal (Costa and Telmer 2007) and using multi-temporal approaches in the Paraná River floodplain (De Morais et al. 2005; Borro et al. 2014). However, only three of the mapping articles addressed wetland conservation specifically, as habitat for wildlife (Ferraz et al. 2007; Rosselli and Stiles 2012) or for protection of rare wetlands such as veredas (Maillard, Alencar-Silva, and Clausi 2008).

The articles related to monitoring objectives referred to diverse topics, related to wetland conservation in some degree. Wetland loss due to infrastructure development has been studied in Argentina (López et al. 2013; Bauni et al. 2015) and mangroves losses due to deforestation in Ecuador (Hamilton and Collins 2013). Wetland degradation has been studied in relation to water quality (Bazán et al. 2005), the presence of cyanobacteria (Ogashawara et al. 2014), suspended sediments (i.e. Mertes, Smith, and Adams 1993), and turbidity evaluation (De Alcântara et al. 2008). Despite their low spatial resolution, time series of normalized difference vegetation index (NDVI) from Advanced Very High Resolution Radiometer (AVHRR) on board of National Oceanic and Atmospheric Administration (NOAA) satellite data have been used to assess biomass dynamics in peatlands (bofedales) of the High Andes (Moreau et al. 2003) and for monitoring seasonal and interannual variability of wetland functioning in the floodplain of the Paraná River (Zoffoli et al. 2008). More recently, time series of the vegetation index from Moderate Resolution Imaging Spectroradiometer (MODIS) have been used to analyse spatio-temporal variability in the floodplains of the Lower (Antico 2012) and Middle Paraná River (Marchetti et al. 2016) as well as in the Pantanal macrosystem (Ribeiro De Almeida et al. 2015).

The wetland hydrological regime has been addressed in articles referring to flood extent, addressing water–vegetation cover interactions particularly with SAR data (i.e. Hess et al. 1995; Grings et al. 2006; Grings et al. 2009; Martinez and Le Toan 2007), and water depth estimation in the floodplains of the Río Negro and Amazon by using interferometry (Alsdorf et al. 2000; Jung and Alsdorf 2010) or altimetry data (León et al. 2006; Da Silva et al. 2010). There also have been experiences with gravimetric data in combination with other sensors to analyse groundwater anomalies and water spatial patterns in the Negro River Basin (Frappart, Seoane, and Ramillien 2013) and to estimate water storage in the Pantanal by integrating precipitation derived from Tropical Rainfall Measuring Mission (TRMM), evapotranspiration obtained from MODIS Evapotranspiration product (MOD16), and analysis of overall vegetation response with enhanced vegetation index (Penatti et al. 2015). Giddings and Choudhury (1989) and later Sippel et al. (1994) were early advocates of the importance of wetland hydrological regime, analysing major river basins using Scanning Multifrequency Microwave Radiometer (SMMR) data from Nimbus-7. A similar approach has been used more recently to estimate the flooded area at monthly intervals for the 'Llanos de Moxos' in Bolivia and 'Llanos del Orinoco' in Venezuela (Hamilton, Sippel, and Melack 2004). The use of microwave sensors is dominant for studies of wetland hydrology.

The modelling of biophysical variables based on remote-sensing signals has been the subject of several studies (Figure 5(a) and (b)). Biomass, leaf area index (LAI), and coverage of *Spartina alterniflora* have been related with field radiometer measurements in the temperate coastal marshes of Bahía Blanca in Argentina (González Trilla et al. 2013). The biomass of different land-cover types was also studied using AirSAR data in the Colombian Amazon (Hoekman and Quiriones 2000), while the quantification of biomass of bofedales was assessed with SAR European Remote-Sensing Satellite (ERS1) data in the High Andes (Moreau and Le Toan 2003). Aragão et al. (2005) conducted a spatial validation of MODIS LAI product on the vegetation of eastern Amazonia. The influence of within-pixel variation in canopy height on the spectral response recorded by Landsat Enhanced Thematic Mapper Plus (ETM+) data was studied in the Amazon rainforest (Hill, Boyd, and Hopkinson 2011). The canopy height of mangrove forests was mapped from Shuttle Radar Topography Mission elevation data, Geoscience Laser Altimeter System (GLAS) on board of Ice, Cloud, and land Elevation Satellite (ICEsat) waveforms, and field data at the Ciénaga Grande de Santa Marta in Colombia (Simard et al. 2008). One contribution on ecological modelling focused on the spatial heterogeneity of phytoplankton using optical data for Lake Mangueira in Brazil (Fragoso et al. 2008), while benthic habitats and submerged vegetation biomass were characterized at Los Roques Archipelago National Park in Venezuela (Schweizer, Armstrong, and Posada 2005). Vegetation structure and inundation patterns in the Central Amazon floodplain (Ferreira-Ferreira et al. 2014) and spatial and temporal variability of macrophyte cover and productivity in the eastern Amazon floodplain were assessed with optical and SAR observations (Silva, Melack, and Novo 2013). Comparatively, few contributions addressed carbon storage and methane emissions, with the exceptions of Melack et al. (2004) that used Japanese Earth Resources Satellite 1 (JERS-1) SAR data and Draper et al. (2014) that used optical and SAR data, both in Amazonia. Regarding the deployment of radiative transfer or statistical models, no studies were found using optical data, whereas three articles focused on electromagnetic simulation models using SAR data in marshes of the Paraná River Delta (Grings et al. 2005; Grings et al. 2008; Grings et al. 2010), for improving the exploitation of SAR data in wetland monitoring (flooding and burning).

Taken together, the published articles on floodplains and shallow lakes addressed the four main objectives identified: mapping, hydrology, monitoring, and modelling. While both optical and SAR data were used to address all aims, SAR observations mainly focused on hydrological studies, while the use of optical data tended to focus on mapping and monitoring.

Regarding remote-sensing systems (Table 3), optical sensors were most frequently used. The preferred platforms for optical sensors were the Landsat series with 55 articles and, to a much lesser extent, Aqua/Terra-MODIS with 10 articles. Image analyses from these sensors were usually based on a single scene or a small number of scenes while

Table 3. Number of articles published about the wetlands of South America by type of journal.

	Number of articles
Remote-sensing journal	
Remote Sensing of Environment	21
International Journal of Remote Sensing	16
IEEE Transactions on Geoscience and Remote Sensing	14
Canadian Journal of Remote Sensing	3
Remote-Sensing Letters	3
Revista de Teledeteccion	3
Remote Sensing	2
Sensors	2
ISPRS Journal of Photogrammetry and Remote Sensing	1
Journal of Applied Remote Sensing	1
Remote-Sensing Applications: Society and Environment	1
Thematic journal	
Wetlands Ecology and Management	7
Journal of Biogeography	6
Journal of Hydrology	4
Aquatic Conservation: Marine and Freshwater Ecosystems	4
Ecological Modelling	3
Estuarine Coastal and Shelf Science	3
Journal of Coastal Research	3
Journal of South American Earth Sciences	3
Advances in Space Research	2
Continental Shelf Research	2
Geomorphology	2
Global Change Biology	2
Hydrological Processes	2
Journal of Geophysical Research Atmospheres	2
Rangeland Ecology and Management	2
Wetlands	2
Aquaculture	1
Archiv fur Hydrobiologie	1
Biogeochemistry	1
Biogeosciences	1
Biological Conservation	1
Bosque	1
Ciencia e Cultura	1
Computers and Geosciences	1
Diversity and Distributions	1
Ecological Engineering	1
Environment, Development and Sustainability	1
Environmental Management	1
Environmental Monitoring and Assessment	1
Environmental Research Letters	1
Fire Ecology	1
Freshwater Biology	1

(*Continued*)

Table 3. (Continued).

	Number of articles
Geophysical Research Letters	1
Hydrology and Earth System Sciences	1
ICES Journal of Marine Science	1
Ingenieria Hidraulica en Mexico	1
International Journal of Ecology and Development	1
Journal of Environmental Management	1
Landscape Ecology	1
Mathematical Biosciences and Engineering	1
Nature	1
Pan-American Journal of Aquatic Sciences	1
Waterbirds	1
Thematic-Brazil journal	
Anais da Academia Brasileira de Ciencias	2
Revista Brasileira de Geofisica	2
Acta Amazonica	1
Acta Scientiarum – Biological Sciences	1
Amazoniana	1
Investigaciones Geograficas	1
Revista Ambiente e Agua	1
Revista Arvore	1

exploitation of time series data remains comparatively rare. Microwave-SAR data were also widely employed (49 articles) and incorporated a larger range of available platforms and sensors. There is a paucity of studies using polarimetric data in wetland ecosystems across the globe (Touzi, Deschamps, and Rother 2009) although satellite data are available from the Phased Array type L-band Synthetic Aperture Radar on board of Advanced Land Observing Satellite (ALOS/PALSAR) since 2006 and from the first airborne polarimetric sensor operated in 1988 (Seasat). None of the reviewed articles addressed data from the thermal infrared region of the electromagnetic spectrum. Large fluvial wetland studies used data from all types of sensors and combinations thereof, while studies of shallow lakes have only used optical data. Research on coastal marshes and lagoons mainly used optical data – particularly Landsat – but in the case of mangrove swamps, optical, SAR, and multisensor approaches have been employed. A novel application related to conservation was the use of Airborne SAR imagery to assess the impacts of stationary fishing gear in north Brazil (Krumme et al. 2015). In Puna and High Andes environments, most studies have used optical data, except for an article focused on biomass quantification of Andean bofedales using ERS satellite SAR data (Moreau and Le Toan 2003).

4. Discussion

Although major cultures of the world have flourished in wetlands, traditionally these ecosystems are still considered unproductive and the foci of disease generation and have been transformed during the past century into places for agriculture, forestry, intensive cattle ranching, urban development, dams, and aquaculture (Reeves and Champion 2004; Galbraith, Amerasinghe, and Huber-Lee 2005). During the 1970s, wetlands started to be recognized as key components for human welfare, and their loss or degradation leads to questions regarding economic development (Ramsar 1971). At the same time, remote sensing has developed rapidly, providing the information and tools needed to pursue local or national wetland inventories, such as the National Wetlands Inventory in the USA. Despite this, the widespread use of remote sensing and its presence in scientific journals have only thrived since the 1990s (Tiner, Lang, and Klemas 2015; Guo et al. 2017). Similar trends were found for wetland research in general from 1991 to 2008, when the annual number of articles published and the number of articles cited increased by more than six and nine times, respectively (Zhang et al. 2010). The results presented for South America mirror these observations: almost no articles were published until the early 1990s, while a mean of 10 articles per year have been published since 2000. When trying to interpret these trends, it is important to consider the Convention of Biodiversity in Rio and the Millennium Ecosystem Assessment between 2001 and 2005 (Millennium Ecosystem Assessment 2005), which highlighted wetlands as the most threatened ecosystems.

In comparison to the global literature on the remote sensing of ecosystems, the number of articles related to the remote sensing of wetlands in South America represents approximately 0.3%. It should be considered that our bibliometric analysis conveys only articles published in indexed journals, so these results are biased to some extent. Conference proceedings and technical reports were omitted because an extensive literature search could not be comprehensive. Nonetheless, such proceedings and reports may represent major contributions. Considering that the area of wetlands in South America is approximately three times larger than the estimated global mean (Junk et al. 2013), it might be expected that a larger proportion of remote-sensing articles concerning ecosystems would focus on wetlands. Nevertheless, forests seem to be the 'charismatic' ecosystems, both in conservation and research efforts, while wetlands and grasslands receive less attention. This fact is also reflected across the remote-sensing literature, where articles focused on forests outnumber those on wetlands or grasslands by ratios of 5:1 to 7:1. In addition, the term 'wetland' was not commonly adopted until recently by the scientific community in South America, which tended to use more specific terms such as floodplains, lakes, shallow lakes, or local terms such as vegas, veredas, or bofedales. The traditional view of wetlands as transitional environments, rather than true ecosystems, has probably contributed to their lack of widespread recognition.

Although the growth in the number of published studies may simply reflect similar trends noted across the globe coupled with growing awareness of wetland ecology and conservation, the expansion of science and technology in many South American countries over the past decade should not be ignored. In this regard, international collaboration is important and desirable, and many researchers from other parts of the globe have established long-standing research agendas in South America. However, the rise in the proportion of authors affiliated to South American institutions is remarkable, especially in the last decade. This suggests a growth in local knowledge and capabilities for remote-sensing research as well as an increase in local interest for studying wetlands.

Most of the articles correspond to wetlands from Brazil and Argentina with a smaller number from Perú and Venezuela, among others. This probably reflects the higher academic and research capabilities of these countries, associated with more developed economies and higher gross domestic product, which impacts on the work conducted in universities and research centres linked to space agencies. Most South American countries have Federal Government Space Agencies, which carry out research programs related to the Earth observation, and are able to manage spatial data acquisition through their own antennas. Some countries have even developed their own satellite missions and are competent to act in the scientific, technical, industrial, commercial, administrative, and/or financial fields for the implementation of space-related policies. Institutes such as the Instituto Geográfico Nacional and the Instituto Gullich in Argentina, the Instituto Nacional de Pesquisas Espaciais in Brazil, and the Instituto Geográfico Agustín Codazzi in Colombia exemplify a long history in the use of satellite data for terrestrial applications. Despite this, South American countries have strong technological and economic constraints when it comes to carrying out long-term programs relating to environmental surveying and monitoring. This reflects not only a long list of social and economic priorities but also perhaps because policymakers often underestimate the association between the health of wetlands and the welfare of the population and the range of ecosystem services they provide to society.

The floodplains of the Amazon and Paraná Rivers along with the Pantanal at the head of Paraguay River are the most studied wetland macrosystems. Several articles focus on other complex macrosystems, including the Apure Llanos in Venezuela and the Araguaia and São Francisco Rivers in Brazil. Wetland macrosystems are landscapes dominated by wetlands and represent distinctive features in South America, commonly associated with the floodplains and basins of large rivers (Neiff, Iriondo, and Carignan 1994; Minotti, Ramonell, and Kandus 2013; Heffernan et al. 2014). In these large wetland macrosystems, it is difficult to discriminate between individual wetlands due to their size and ubiquity. They usually present a mosaic of wetlands with different structures, dynamics, and degrees of connectivity that provide additional complexity to the hydrological regime. Although the three wetland macrosystems that dominate most of the published articles have similar features, they exhibit important differences from geographical, hydrological, and ecological perspectives. In all three regions, the focus of the studies was reasonably consistent which included mapping, monitoring, modelling of biophysical variables, flood extent, and hydrological analysis. However, the number of articles published still seems insufficient to account for the spatial and temporal complexity of these macrosystems. The diversity of these contributions suggests that it may be possible to compare data products and approaches developed specifically for each macrosystem in order to support regional long-term monitoring and inventory strategies. In this respect, there are notable contributions, such as Hamilton, Sippel, and Melack (2002) which compares the floodplains of the most important rivers in South America, Hamilton, Sippel, and Melack (1996, 2004) which compares seasonal inundation patterns in two large savanna floodplains – the Llanos de Moxos (Bolivia) and the Llanos del Orinoco (Venezuela and Colombia), and Thieme et al. (2007) which investigates conservation planning in data-poor areas such as the Madre de Dios River in Perú and Bolivia.

Studies on coastal wetlands were in minor proportion (19%) and addressed mapping (land-cover types, landforms, and vegetation), monitoring (land-cover changes, wetland loss, and geomorphological and hydrological dynamics), and modelling, as these are of particular interest for coastal wetland conservation and management. South American coastal wetlands are highly threatened by human actions including intense agricultural production, the development of tourist infrastructure, and the expansion of urban areas (Bildstein et al. 1991; Dias et al. 2013). In addition, coastal wetlands are highly vulnerable to climate change, which is already causing sea level rise and increased storm intensities (Diez, Perillo, and Piccolo 2007; Pousa et al. 2007; Twilley 2007; Tosi et al. 2013). Mangroves cover 45,400 km^2 of coasts in South America, mainly along the Atlantic Ocean, which equals to 27% of the global mangrove area (De Lacerda 2002). In addition, extended coastal lagoons, sand beaches, and salt and brackish marshes occur along the temperate coasts, mainly with Spartina spp. and Sarcocornia spp. The predominant data used to study salt marshes was optical, particularly Landsat, whereas studies on mangroves included a variety of sensors in the optical and microwave spectrum including SAR, on board satellites and airborne sensors, highlighting the existing interest in knowledge and conservation of these tropical ecosystems.

The remaining articles focused on isolated inland wetlands. The single wetland body is the most common view or conceptualization of a wetland ecosystem and is often the one that determines the criteria used for the classification of wetlands. In such a scenario, the landscape matrix typically consists of terrestrial ecosystems and wetlands occur as isolated entities (Benzaquén et al. 2013; Junk et al. 2014). Shallow lakes and Puna wetlands in 24 articles represent this type of wetland. These works focused on wetland delineation and vegetation mapping, monitoring water quality, wildlife habitat, and drainage impact for productive purposes. No publications on peatlands were found, despite the importance of these ecosystems in Patagonia (Blanco and De La Balze 2004).

The articles reviewed in within this bibliometric study demonstrate the wide variety of data types, sensors, and strategies used to study wetlands in South America. The amount of research conducted with optical and SAR data in these ecosystems is reasonably balanced. Landsat images dominated the use of optical, whereas the diversity of SAR sensors used with different beam modes and technical characteristics was remarkable. SAR data were predominately used for flood delineation and hydrological studies, but mapping, monitoring, and modelling of biophysical variables have been stated as objectives of the studies as well.

Spatial resolution is a clear limiting factor for the remote sensing of wetlands, both for landscapes where wetlands are single patches or where the landscape is a mosaic of wetlands (i.e. wetland macrosystems). The need for high-resolution imagery is not only motivated by their size but also their enormous internal spatial heterogeneity. There were some particularly interesting articles using IKONOS imagery. Arieira et al. (2011) integrated field sampling, geostatistics, and remote sensing to map wetland vegetation in the Pantanal. Barbosa and Maillard (2010) assessed the potential of a new region-based classifier for mapping a wetland complex in the Brazilian savanna. Pratolongo et al. (2013) analysed land-cover changes in tidal salt marshes of Bahía Blanca estuary in Argentina during the past 40 years by comparing remote-sensing imagery with aerial photographs. Galvao et al. (2003) characterized the spectral reflectance of shallow lakes from the Brazilian Pantanal with field and airborne hyperspectral data. Unfortunately, high-resolution imagery is expensive and usually beyond the means of institutions in South America.

Another limitation is that high-resolution optical images are not acquired at regular intervals, so no robust time series exist for the analysis of the temporal variability, which is critical for the study of wetlands. Of the low spatial resolution studies, noteworthy contributions relate to time series of green indices data products derived from NOAA-AVHRR and MODIS observations made for monitoring biophysical variables and for macrosystems dynamic studies (Moreau et al. 2003; Zoffoli et al. 2008; Antico 2012; Ribeiro De Almeida et al. 2015; Marchetti et al. 2016). Another remarkable approach is the use of multi-temporal series of Landsat data to aid in the analysis of historical change and systems characterized by interannual or interdecadal variability (Borro et al. 2014). A noticeable experience is the one recently obtained in Colombia, as part of its wetland inventory program (Estupinan-Suarez et al. 2015), which has made huge efforts to delimit wetlands and integrate a conceptual framework for wetland function by using existing maps and optical data (MODIS NDVI profiles from 2007 to 2012 and ALOS PALSAR data from 2007 to 2010).

Finally, it should be emphasized that there is a lack of research using thermal sensors. This variable is critical when analysing functional aspects of wetlands, especially in floodplains, where water pulses can be coupled with thermal pulses, affecting population dynamics of the biota, which in turn affect the functioning of ecosystems.

5. Conclusions

During the past decade, there has been a substantial increase in the number of articles related to the remote sensing of wetlands in South America. Even though this increase appears to reflect improvements in the technological and scientific capacities of several countries in the region, there appears to be unresolved issues within the remote-sensing community. The number of articles published does not reflect the extent of wetlands in South America, but their focus does reflect the diversity of wetland types found across the continent. Wetlands are also challenging targets to map and monitor because of their spatial, temporal, and spectral complexity (Gallant 2015; Tiner, Lang, and Klemas 2015).

Most of the published articles focus on large fluvial wetlands and, although there are examples of research in other type of wetlands, these are isolated and scattered. Considering the diverse aims of the articles, the variety of wetland types, and the considerable areas covered by macrosystems, it is reasonable to ask whether the available methodologies proposed by these study cases can be standardized across the continent with sufficient levels of accuracy and consistency to set wetland inventories and monitoring schemes. For wetlands in general, doubts have been raised about this possibility (Gallant 2015), while in the case of South America, the effort made to publish articles does not seem to be accompanied by concrete policies on conservation action and management. In addition, it would be desirable to develop regional cooperation programs, comprehensive survey protocols, and long-term monitoring procedures. Based on the widespread availability of freely accessible images as well as on the potential opportunities afforded by new SAR data, and considering the need for wetland management tools, a multi-resolution, multi-temporal, and multi-sensor approach would appear to be the most promising option for addressing the spatio-temporal complexity of wetlands in South America.

Despite the short history of remote sensing in wetlands of South America, the numbers and trends in the publication of scientific articles are promising. However, one cannot ignore that the economic and political fluctuations of the South American countries determine instability of scientific–academic activity, as well as policy and management of natural resources, with negative impacts on the medium- and long-term planning.

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