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Mapping and spatial characterization of Argentine High Andean peatbogs

Andrea E. Izquierdo · Javier Foguet · H. Ricardo Grau

Abstract Peatbogs are the most productive and biodiversity rich ecosystems of high dry Puna region, and provide essential ecosystems services to local inhabitants. Despite their ecological and economic importance, the geographic patterns and distribution of peatbogs as well the dynamic of this system are barely known. In this work we (1) identified and mapped subtropical Argentine High Andean peatbogs based in a supervised classification of Landsat images, and a posteriori spatial processing to define functional units; (2) used such classification to characterize the whole Argentina Puna region (14.3 million hectares) in terms of their geographic patterns of peatbogs; and (3) characterized the region's sub-watersheds according to their peatbogs density and geographic characteristics. The post-process map reports a total area of peatbogs of 94427.55 ha (0.66 % of total study area) with 10,428 polygons. The majority of peatbogs are small or median (i.e., 21.8 % of total area included <10 ha, while 24.5 % of total area are peatbogs from 10 to 50 ha), but only two peatbogs with >10,000 ha represent 18 % of total area. Peatbogs density is spatially heterogeneous, with much higher density in the north and central east of the study area. Sub-watershed can be grouped into six main groups according to the percentage of peatbogs cover, mean size of peatbogs and altitude. The combination of basic information, such as map of peatbogs cover with spatial patterns characterization, is a priority input for the conservation planning of this extensive and valuable ecosystem, and to ongoing land use planning initiatives.

Keywords Peatbogs · High Andean wetlands · GIS · Landscape planning · Puna

Introduction

High-elevation peatbogs are key functional units in the arid environments of the Puna region of subtropical South American Andes (Squeo et al. 2006a). Due to their high soil moisture, they support much of the region's biodiversity (Ruthsatz 1993; Squeo et al. 2006a) despite they are near the ecophysiological limit of terrestrial life. They contribute a significant proportion of primary productivity (Baldassini et al. 2012), maintain vertebrate populations (Halloy 1991; Seimon et al. 2007), and regulate hydrological resources, which in some cases are very important for urban and agricultural areas downstream (Reboratti 2006). Such features are common to other high elevation dry lands of the Andes (Central Chile and Argentina, western Bolivia, southern Peru) and around

A. E. Izquierdo (✉) · H. Ricardo Grau
CONICET, Buenos Aires, Argentina
e-mail: aeizquierdo@gmail.com

A. E. Izquierdo · J. Foguet · H. Ricardo Grau
Instituto de Ecología Regional-UNT,
San Miguel de Tucumán, Argentina

the world, including the Tibetan and peri-Himalayan plateaus and high watersheds.

The region has been historically affected by grazing, while in the present climate change and mining prospects appear as the main potential threats to biodiversity and hydrological function. During the past decades, human and livestock pressure in the region has decreased (Izquierdo and Grau 2009), which likely resulted in a recovery of ecosystems and their wildlife (Grau and Aide 2007). However, this relatively favorable situation for nature conservation with decreasing conflicts with productive activities may no longer be guaranteed. Future climate change scenarios identify high-elevation ecosystems among the most vulnerable (Beniston et al. 1997; Vuille et al. 2008, Urrutia and Vuille 2009; Herzog et al. 2012), and the combination of global markets and domestic policies suggests mining could expand significantly in the region with potentially vast impacts on water cycles. Despite their ecological and economic importance, the geographic patterns of peatbogs and the dynamics of this system are barely known.

Mapping is a first and necessary step to carry out a wide range of tasks aiming to knowing, understanding, and managing this system, including natural resources inventory, habitat characterization, modeling of biodiversity patterns, zonation of risks and conservation priorities, and environmental monitoring over time (Adam et al. 2010). Watersheds include networks of peatbogs functionally connected, and as such they are useful units for decision making and land use planning. Argentina is currently involved in a process for developing a National Wetlands Inventory promoted by the recently approved by the National Senate, National Wetlands bill 1.628/13. This initiative will need detailed maps for land use planning and management guidelines. However, there is not previous effort in the region to generate comprehensive maps based on remote sensing techniques.

From a remote sensing perspective, high Andean peatbogs are very contrasting with their surrounding matrix by having plant cover usually greater than 70 % and high plant productivity (Squeo et al. 1993, 2006b). They are typically located in depressed topographic terrain, where high soil moisture combined with low rates of decomposition associated to low temperatures, results in a particular type of vegetation and soils. The spectral characteristics of peatbogs make them relatively easy to remotely discriminate from their much drier and less productive surroundings, and to classify them in satellite images. In addition to spectral features, low levels of cloudiness and atmospheric haze characteristic of these arid high-elevation environments further facilitate the use of satellite imagery. In contrast, morphological patterns associated with complex geological and topographic characteristics of mountains lead to difficulty in precise delimitation and spatial configuration of functional units.

Based on good quality mapping of these units, important ecological features can be derived, including patterns of peatbog density through the region, size distribution, distribution along environmental gradients, and distribution across watersheds: the functional hydrological geographic units. To contribute to such goals in this work, we (1) identified and mapped subtropical Argentine High Andean peatbogs based in a supervised classification of Landsat images (30 × 30 m resolution), and a posteriori spatial processing to define functional units; (2) used such classification to characterize the whole Argentina Puna region (14.3 million hectares) in terms of their geographic patterns of peatbogs; and (3) characterized the region's sub-watersheds according to their peatbogs density and geographic characteristics. By complying with these objectives, we provide a first regional comprehensive spatial model of peatbogs distribution that can be used for local planning initiatives, and a methodological procedure that can be applied to other high elevation regions around the world.

Methodology

Study area

This study covered the Puna and High Andean ecoregions of northwestern Argentina, an area of approximately 14,300,000 ha (Fig. 1). These ecoregions extend into high elevation Andean environments of northern Chile, southwestern Bolivia, and southwestern Peru (Olson et al. 2001). Our study area is bounded on the north and west by international borders (i.e., between Argentina and Bolivia, and Argentina and Chile, respectively) on the south by southern boundary of San Guillermo Biosphere Reserve,

Fig. 1 Study area peatbogs' map resulting from post-processed classification in Northwest of Argentine and location in South America (*inset*)
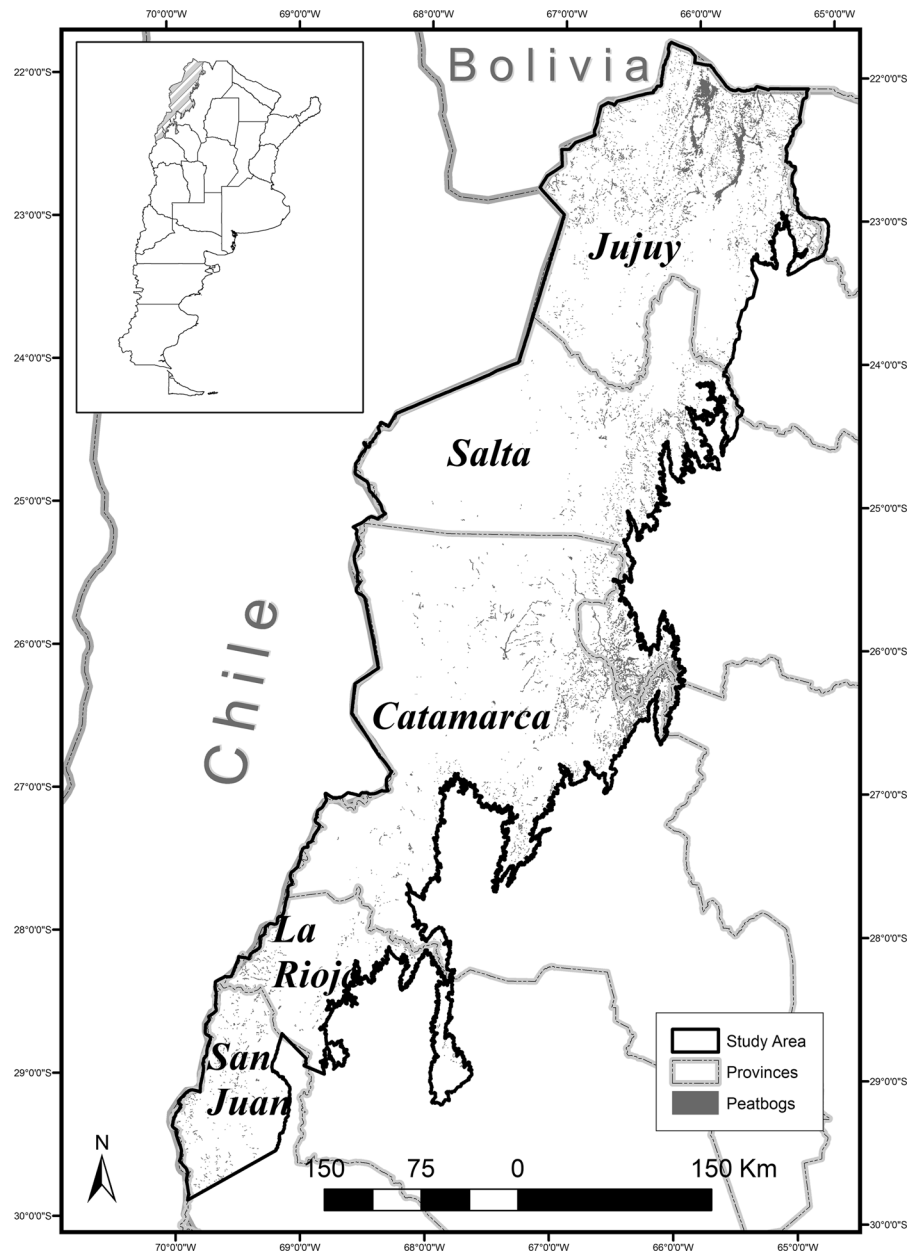
while the east boundary was defined mainly by the 3200 masl following provincial or watersheds boundaries. East boundary, based on an elevation line, allows both to include high-elevation peatbogs, and to limit the inclusion of agriculture lands, which could be confused with peatbogs in the classifications. Peatbogs located over the border (mostly in the eastern side of the study area) were fully included in the analyses (implying that some of them included parts below the

3200 masl elevation line). The resulting study area includes an elevation range from 3179 masl (in internal endorheic basins) to approximately 6900 masl in the top of the highest mountains. Climate is very dry with average annual precipitation ranging between 100 and 400 mm and mean annual temperatures from of 9° to −4° (Cabrera 1976).

Outside the peatbogs, vegetation occurs within a matrix of bare soil, and is characterized by sparse

grasslands (*Calamagrostis*, *Agrostis* and *Festuca bunchgrasses*) and sparse short shrublands *(Parastrephia, Fabiana, Acantholippia, Adesmia)*(Fig. 2a). When water is available in association to depressed topography, we find the cushion bogs named "*bofedales*," "*vegas*," or peatbogs (Fig. 2b). Peatbogs are a key unit of the region concentrating plant productivity and regulating the hydrological cycle. These formations occur at elevations between >3200 to 5200 masl. Peatbog vegetation includes cushion plants often growing in high-water table conditions. Large cushions are dominated by *Distichia muscoides*, *Oxychloe andina,* and *Plantago rigida*. Other genera include *Gentiana*, *Hypsela*, *Isoetes*, *Lilaeopsis*, *Ourisia*, and *Scirpus*. In well-drained areas, some of the cushion plants include *Azorella compacta* and *Werneria aretioides*. These topographic and vegetation characteristics are very contrasting with the surrounding landscape in terms of vegetation cover and photosynthetic activity (Fig. 2c, d) which facilitates the classification and make the peatbogs a key support for the biodiversity and human population in the region (Fig. 2d, e).

Methods

We identified peatbogs in study area using a supervised classification of Landsat TM images with
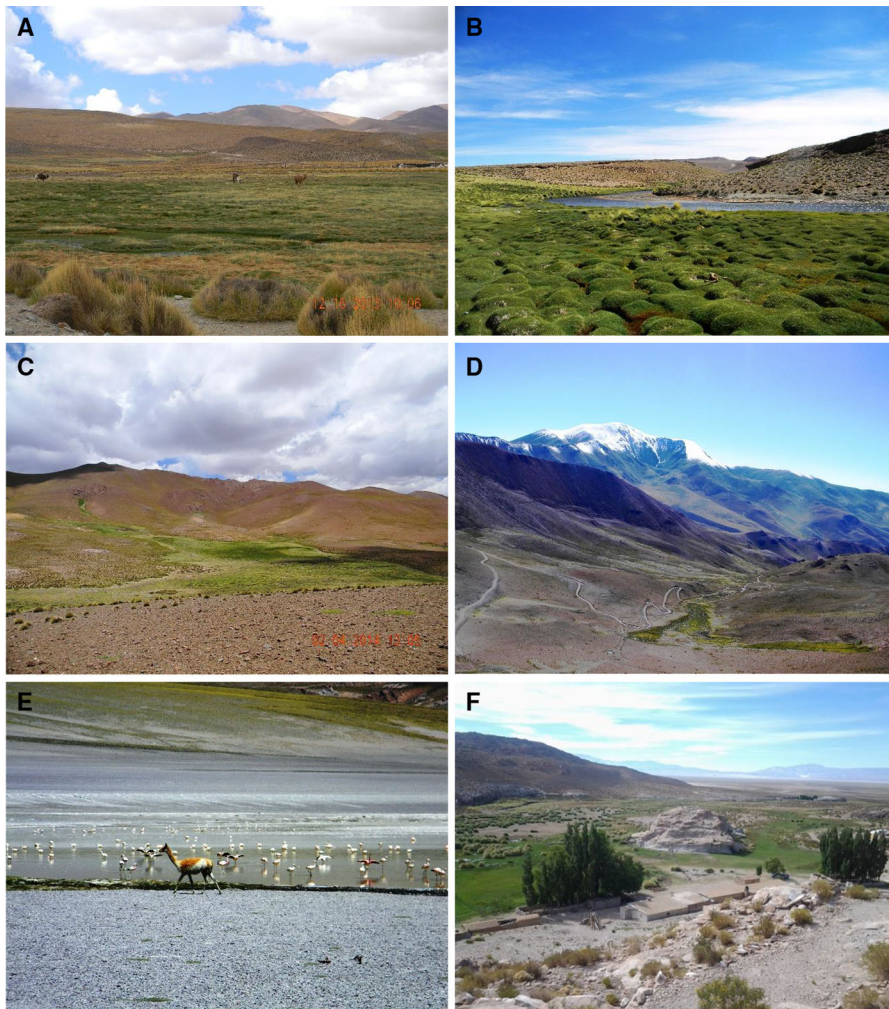
Fig. 2 Typical peatbog's vegetation on cushion bogs (**a**, **b**) and topographic characteristics (**c**, **d**). Peatbogs are key support environments for biodiversity (**e**) and human population (**f**) in the region

30×30 pixel and LT1 pre-processing level. We classified a mosaic of 19 Landsat 5 images included between paths 231 and 233, and between rows 75 and 81, and one Landsat 8 (232/80). The Level 1T (L1T) data product provides systematic radiometric accuracy, geometric accuracy by incorporating ground control points, and employs a digital elevation model (DEM) for topographic accuracy (http://landsat.usgs.gov/descriptions_for_the_levels_of_processing.php). To construct cloud-free mosaics, we used scenes of different years (2009–2013); and to maximize the contrast between peatbogs and the surrounding matrix we used scenes of summer and early autumn (rainy season) months (January–April). We used the following scenes: Landsat 5TM: March 2010 (231/75, 231/76, 231/77), April 2011 (231/78), February 2008 (231/79), February 2009 (232/75), February 2010 (232/76, 232/77, 232/78, 232/79), January 2009 (233/77, 233/79), February 2009 (233/78), March 2011 (233/80), February 2011 (233/81); and Landsat 8: April 2013 (232/80).

For the supervised classification, we used the maximum likelihood method to discriminate between two categories: Peatbog and No Peatbog. We used Google Earth® images to screen-digitalize paired polygons of the two categories across the study area, which were used as training points by the classifier algorithm. Because peatbogs characteristics (i.e., topography and vegetation very contrasting with the surrounding landscape) identifying peatbogs using Google Earth is very accurate (Fig. 3c). The digitalized polygons in Google Earth were exported from kml format to ArcGIS shape and reprojected to WGS_1984_UTM_Zone_19S which was the coordinate systems used in our analysis.

We processed the classified output raster sequentially using the "sieve," "clump," and "region group" functions to improve the classification quality. The "sieve" function was used to eliminate isolated pixels, "clump" function to reduce fragmentation by smoothing the ragged class boundaries and clumping the classes, and "region group" to final grouping of peatbog class pixels. This resulting map was considered the "original classification." The original classification was converted into shape files and then it was post-processed by means of the "aggregate polygons" tool at different distances (100, 300, and 400 m). "Aggregate polygons" function combines polygons within a specified distance to each other into new polygons. This tool is intended for moderate scale reduction and aggregation when input features can no longer be represented individually due to, in our case, major resolution required to map intra-heterogeneity of peatbogs or topographic characteristics such as canyons or ravines. Finally based on a sensitivity analysis, we selected the better map based on parameters that improved the aggregation of functional units (i.e., peatbogs) such as, number of polygons, area, mean total edge, and mean perimeter/area. For this, we digitalized a new set of 53 spatially randomized peatbogs (i.e., different from the training polygons) distributed across all size ranges on Google Earth® and compared them with the corresponding polygon(s) resulting from the original classification and post-classified maps. This approach allowed us to include an extensive and widely distributed collection of ground control points. Quickbird images in Google Earth® are very reliable for visual identification with a high spatial resolution, but they do not allow quantitative spectral analyses; so they can be used as "ground truth" to validate classifications conducted with methods based on reflectance-based digital numbers derived from other images. This methodological approach is widely used since Google Earth® high-resolution images are available (see for example Izquierdo et al. 2008; Potere 2008; Cha and Park 2007; Yua and Gong 2012). Comparison between digitalized peatbogs and post-classified maps was based on standard landscape indices of shape (i.e., number of polygons, area, total edge, mean perimeter/area) of the resulting peatbog polygons of each post-processed map with the 53 digitalized "test" polygons. We selected the Aggregate polygons 300 m post-classified map as the final peatbogs' map because although the map with 400 m of threshold differed the least in number of polygons, the mean perimeter/area differed more implying a larger disagreement in the description of the peatbogs' shape (Table 1). In addition, the total number of polygons in Aggregate polygons 400 m maps was 8597 implying some level "over clustering" resulting from joining several polygons belonging to functionally different peatbogs (Table 1).

To assess the final map's accuracy, we constructed a 10-km grid of points covering the study area. At each intersection (1400 points, regularly distributed), we determined the cover category (1373 No Peatbog and 27 Peatbog), to which we added 513 additional Peatbog points purposely located to be well distributed

Fig. 3 Original (**a**) and post-processed classification (**b**) comparison in one particular peatbog system. **c** Peatbog image on Google Earth; and **d** NDVI (normalized vegetation index) from Landsat images
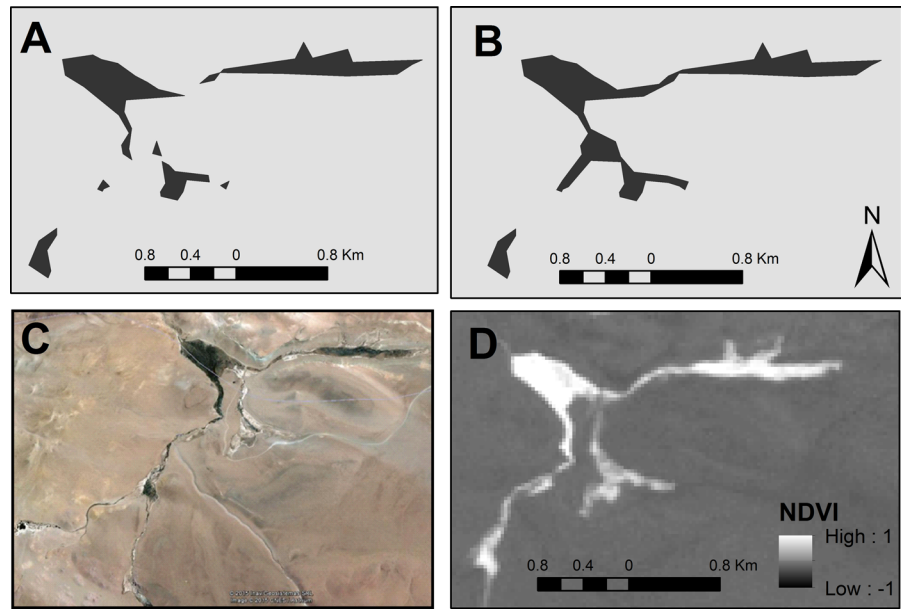
Table 1 Assessment of number and shape parameters (area, total edge, and mean perimeter/area) of 53 ground polygons in comparison with the original and post-classified maps

	N° polygons	Area (ha)	Total edge (km)	Mean per-area (km)
Digitalized polygons	53	1083.8 (1045.9)[a]	252.01 (236.3)[a]	56.4 (51.13)[a]
Original classification	112 (18,071)[b]	363.5	109.6	90.7
Post-classification				
100 m	87 (13,331)[b]	383.2	111.2	71.6
300 m	66 (10,429)[b]	444.2	119.2	58.8
400 m	55 (8597)[b]	544.2	210.3	41.1

[a] Without 9 polygons no classified

[b] Total number of polygons of study area

Table 2 Accuracy assessment of original classification and post-classification maps

	Original classification		Post-classification	
	Peatbog	No peatbog	Peatbog	No peatbog
Peatbog	355 (65.7 %)	185	384 (71 %)	156
No peatbog	1	1372	3	1370
Total	18071[a]	–	10429[b]	–
Accuracy	82.5 %		85.5 %	

[a] With 10,876 polígonos <1 ha

[b] With 4593 polígonos <1 ha

across the study area. These "ground" points were compared with "original classification" and with "final peatbog map" (Table 2). Because we found a

proportional error between mapped area and digitalized area -i.e., "real" area (see "Results" section), we used the linear function representing this proportion to

correct the estimate of peatbog area from the final peatbog map, i.e., the Aggregate polygons 300 m post-classified map.

We characterized peatbogs based on morphologic and environmental variables: landscape metrics of shape and continuity (structural connectivity), altitude, and climate (mean annual precipitation, mean annual temperature). Landscape metrics were calculated with Patch Analysis©; continuity with the "near" function, and altitude based on DEM through ESRI@ ArcGIS10.1. A "gravity index" of isolation was calculated to each peatbog based on the following formula: nearest-neighbor Area/nearest-neighbor distance[2]. Climate variables were obtained from WorlClim 1.4 (http://www.worldclim.org/).

Finally we analyzed the spatial distribution of peatbogs on sub-watersheds of the study area. Based on national watersheds maps (http://www.ign.gob.ar/sig), we sub-divided the five main watersheds that include the study area into sub-watersheds using automatic delineation based on DEM method. We used the SRTM 90 m Digital Elevation Database v4.1 and post-processed the automatic delineation for merging and manual editing boundaries to match boundaries with national watersheds. This process resulted on 32 sub-watersheds for the study area. We grouped sub-watersheds with hierarchical classification (i.e., Cluster Analysis with Pc Ord© 5) based on parameters of the following peatbogs geographic features: percent of area covered by peatbogs, altitudinal range, mean altitude, size range, mean size, distance to nearest neighbor, and gravity index of peatbogs.

Results

Classification procedure

The original classification of Landsat images yielded 67,335 ha classified as peatbogs (0.47 % of total study area) included in 18,071 polygons (Fig. 1). Many of these polygons occurred in close proximity, and are clearly part of the same functional peatbog (Fig. 3a). The post-classification process (300 m threshold) resulted in the aggregation of polygons of the same hypothetical peatbog (Fig. 3b) and in the reduction of the total number of polygons to 10,429 (Table 2).

The total accuracy of final peatbog map was 85.5 %, in comparison with 82.5 % in the original classification (Table 2). The accuracy assessment showed that 65.7 % of the original classification peatbogs were correctly classified and improved to 71.3 % after the post-classification process. Points of no peatbogs were almost 100 % correctly classified (Table 2), implying this is a "conservative" map of peatbogs. Validation by digitalized polygons showed that of the 53 digitalized peatbogs; 9 (17 %) were not correctly classified in the original classification (consequently they were not post-processed) (Table 1). From the remaining 44 functional units (i.e., peatbogs) present on the two maps (i.e., correctly classified), 21 improved on the number of polygons that form a functional unit; and of these, 17 reflected more accurately the considered variables in the post-processed map and four did not differ between post-processed and original classification (Table 1).

We selected the Aggregate polygons 300 m as a better post-processed classification. This map depicts a total area of peatbogs of 94427.55 ha (0.66 % of total study area) (Table 2). Although the validation by point improves with post-classification, the area of peatbogs is still underestimated (Table 1). Since the underestimation is significantly and linearly related with individual peatbog area (R^2 0.98, $p < 0.0001$), we calculated an area correction factor to use on landscape analysis based on linear regression ($Y = 2.44 + 1.44 \times X$, where Y is estimated area and X is area on post-classified map). Considering this correction, the total estimated area was 161,402 ha (1.13 % of total study area).

### Geographic patterns of peatbogs

Individual peatbogs ranged in size from 2.6 to 14,794 ha, with a mean size of 15 ha and a median of 5.03 ha (Table 3). The number of polygons decreased exponentially with their area (Fig. 4a). Forty-two percent of the total area was included in the 10,067 polygons smaller than 50 ha (Fig. 4b). Only two peatbogs are >10,000 ha but they represent 18 % of total area.

Peatbogs are distributed between 3005 and 5141 masl, with a mean elevation of 4056 masl (Table 3). Estimated annual precipitation and temperature, respectively, range from 30 to 339 mm and from −0.8 to

Table 3 Biogeographic and climatic parameters of mapped peatbogs in study area

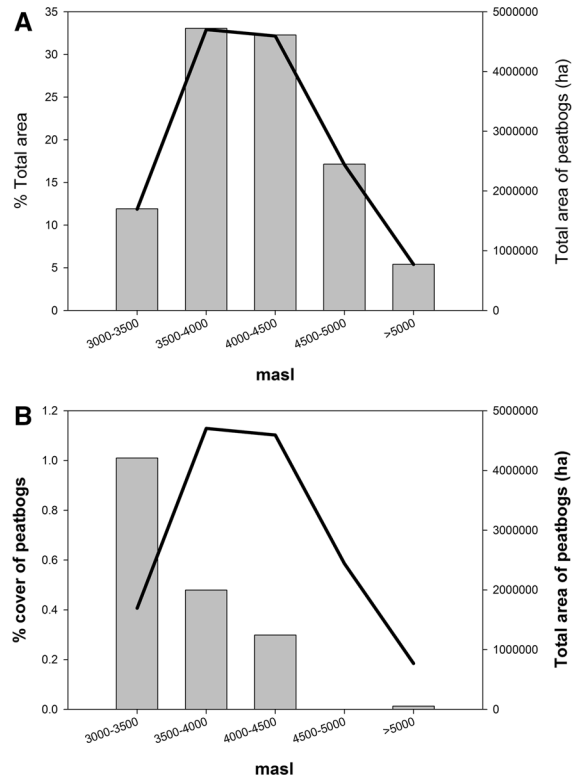|	Estimated area ha	Mean altitude (masl)	Mean ndvi	Mean precipitation (mm)	Mean temperature (°C)
Min	2.57	3005.5	−1.00	30	−0.8
Max	14793.65	5141.4	0.73	339	12.25
Mean	15.48 (5.03[a])	4056.07	0.23	109.4	6.00
STD	2.70	375.12	0.10	48.26	2.40

[a] Median
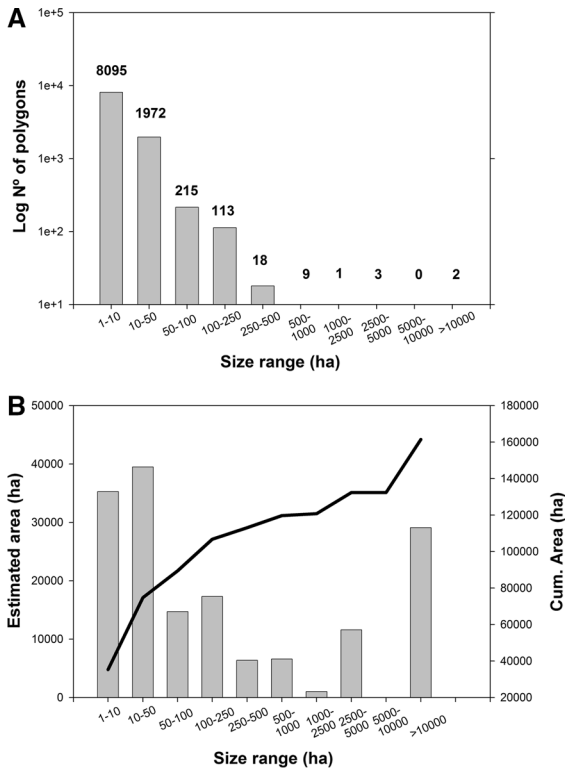
Fig. 4 Size distribution of peatbogs with total number of polygons in each range (**a**) and estimated and accumulative area (**b**) in different size classes

Fig. 5 Percent of peatbog's cover (**a**) and total area of peatbogs (**b**) by altitudinal range of study area

12.2 °C, with a mean of 109.4 mm and 6 °C, respectively (Table 3).

Thirty-three percent of the total area of peatbogs occurs between 3500 and 4000 masl and 32 % between 4000 and 4500 masl (Fig. 5a). While the altitude range with higher cover of peatbogs is from 3000 to 3500 masl (Fig. 5b). Above 5000 masl, peatbogs cover only 0.002 % of the area but, since the total area in this elevational range is much smaller, it represents 5.5 % of the total elevation range's area (Fig. 5). Peatbogs location is not evenly distributed across the study area (z-score = −82.04, $p < 0.01$) with an observed median distance between nearest

neighbor of 463 m (mean = 741 m). Higher peatbog density occurs in the north and central east of the study area (Fig. 6).

Watersheds classification

From 32 sub-watersheds on the study area, "*Laguna de los Pozuelos*" and "*Santa Maria*" sub-watersheds have the larger percent of area covered by peatbogs (6.16 and 4.2 % respectively, Table 4); while the highest number of peatbogs occurred in the "*Calchaqui*" sub-watershed (1337 peatbogs that cover 1.97 % this sub-watershed), "*Guayatayoc-Miraflores*" (904 peatbogs on 3 % sub-watershed area) and "*Laguna de*

Fig. 6 Density distribution of peatbogs into sub-watersheds. Density is the number of peatbogs' pixel by the total area within a window of 25 km radio
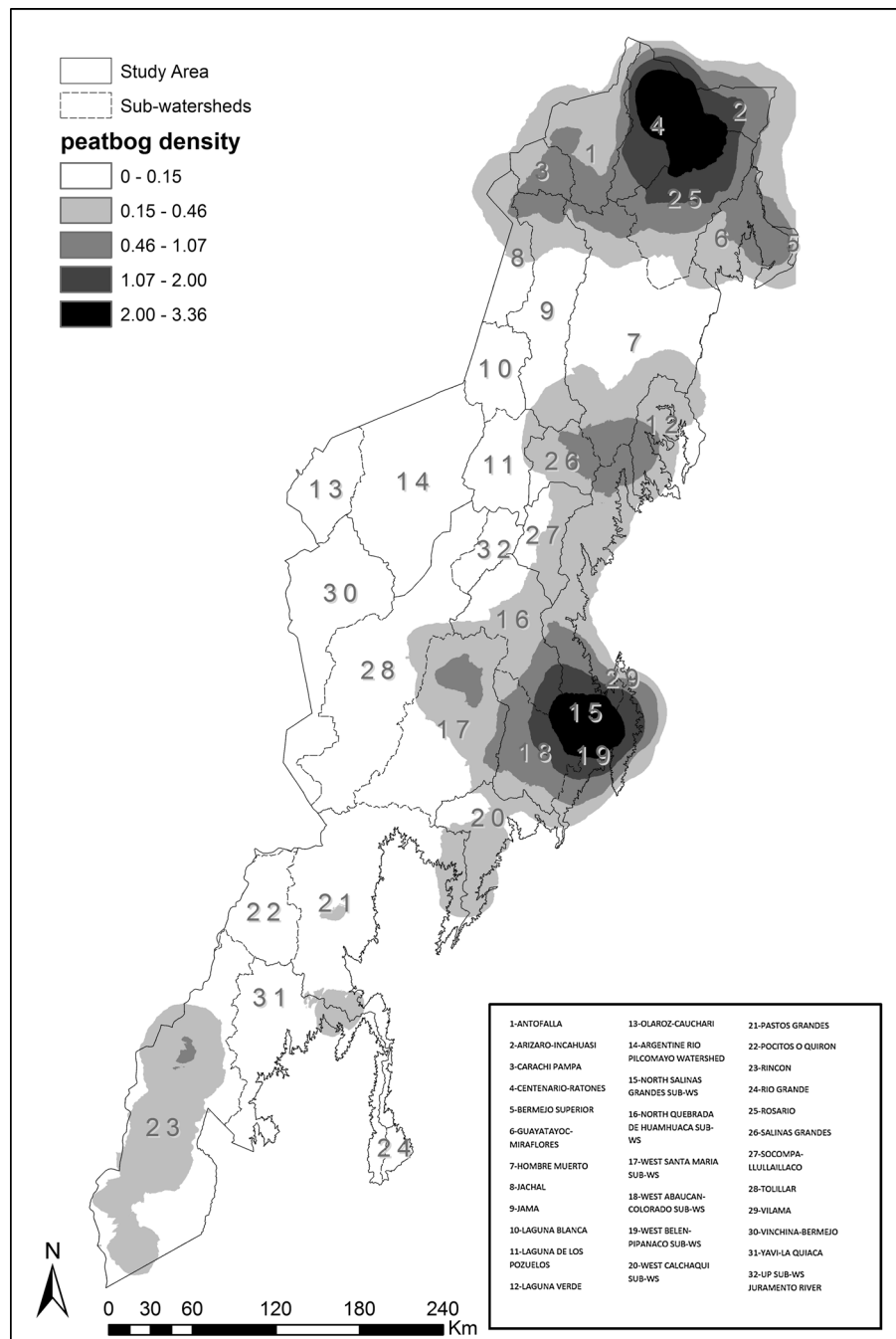
los Pozuelos" (886 peatbogs on 6.16 % sub-watershed area). "*Tolillar*," "*Laguna Verde*," "*Rincón*," "*Arizaro*," and "*Centenario-Ratones*" are the sub-watersheds with low density and more isolated peatbogs (Table 4).

The cluster analysis of sub-watersheds based on percentage of cover, altitudinal range, mean altitude,

size range, mean size, distance to nearest neighbor, and gravity index of peatbogs resulted in six groups (Fig. 7). Clusters are grouped mainly by the percent of peatbogs cover; mean size of peatbogs and altitude. Group 1 includes two sub-watersheds in the north of the study area ("*Guayatayoc-Miraflores*" and "*Pozuelos*") with highest percentage of area covered by

**Table 4** Number, percentage area, mean near distance, and mean gravity index by watershed

Sub-watershed	Peatbogs	Area peatbogs %	Mean near distance m.	Mean gravity index
Antofalla	105	0.06	756.42	0.56
Arizaro-Incahuasi	12	0.01	756.21	**0.15**
Carachi Pampa	297	0.32	622.17	1.23
Centenario-Ratones	124	0.14	**1147.19**	**0.22**
Rio Bermejo Superior	49	1.17	790.86	40.22
Guayatayoc-Miraflores	904	2.96	777.25	12.03
Hombre Muerto	289	0.43	648.53	1.29
Jachal	819	0.25	947.45	0.40
Jama	177	0.41	924.27	2.10
Laguna Blanca	680	1.23	549.30	1.91
Laguna de los Pozuelos	886	6.16	628.81	38.23
Laguna Verde	5	0.01	**1442.02**	**0.07**
Olaroz-Cauchari	298	0.15	801.28	0.35
Argentine Pilcomayo Ws	476	0.35	652.40	21.85
North Salinas Grandes Sub-Ws	15	0.21	802.08	0.24
North Quebrada de Humahuaca Sub-Ws	544	1.17	724.81	2.91
West Santa Maria Sub-Ws	676	4.25	590.81	1.91
West Abaucan-Colorado Sub-Ws	339	0.13	**1052.71**	0.34
West Belen-Pipanaco Sub-Ws	216	0.30	898.31	0.41
West Calchaqui Sub-Ws	1337	1.97	710.47	1.53
Pastos Grandes	195	0.51	797.85	0.69
Pocitos o Quiron	35	0.03	915.98	0.47
Rincon	59	0.06	**1190.84**	**0.11**
Rio Grande	9	0.01	946.64	0.53
Rosario	339	0.66	745.26	0.59
Salinas Grandes	644	0.20	904.49	0.63
Socompa-Llullaillaco	0	0.00	0	0.00
Tolillar	18	0.04	**1091.57**	**0.06**
Vilama	210	0.55	732.98	23.66
Vinchina-Bermejo	162	0.11	908.12	0.29
Yavi-La Quiaca	526	2.72	594.55	40.26
Juramento	3	0.32	358.96	0.54

peatbogs and very large peatbogs at low altitude (Fig. 7). Another group, located in the central east and northeast, was formed by sub-watersheds with high percentage of peatbog's cover and at low altitude, but smallest peatbogs. The majority of sub-watersheds fell within a group with low percentage of peatbog's cover and low median size and altitude. "Laguna Verde," "Rio Grande," "Vinchina," and "Juramento" were grouped together by having isolated peatbogs and low percentage of cover, while "Tolillar," "Rincon," "Abaucan-Colorado," "Belen-Pipanaco," "Jachal,"

and "Vilama" were characterized by isolated peatbogs with the wider altitudinal range. "Socompa" watershed was singled out as the only watershed without mapped peatbogs (Fig. 7).

Discussion

The contrasting spectral characteristics of peatbogs and their surrounding environments in the study area (Fig. 3) allowed us to map peatbogs over large region
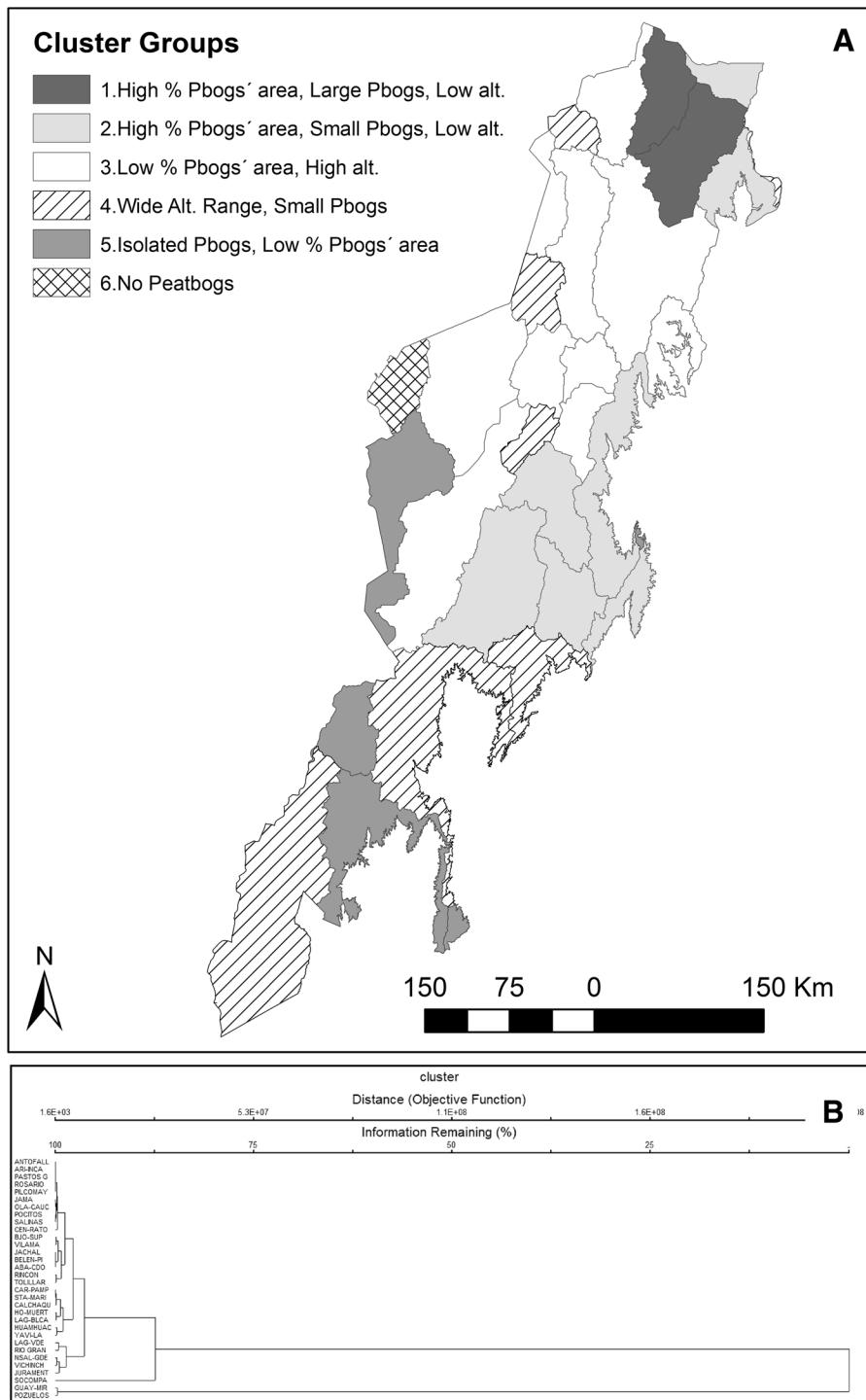
Fig. 7 Groups of watersheds (**a**) originated in cluster analysis dendrogram (**b**) based on percent cover area, altitude, size, and isolation of peatbogs

with reasonably good accuracy levels and to improve the original classification with a GIS-based post-processing procedure (Table 1; Fig. 3). Post-processing increased the accuracy of the spatial model,

especially in quantifying the number of polygons (Table 1; Fig. 3) which is an important variable to define functional unit's for geographic and management assessments. Other studies have developed different approaches to improve the accuracy of image classification (Domacx and Suzen 2006; Yang 2007) showing the importance of post-processing to improve the outputs aimed to decision making. However, these studies were on forest regions and we found few studies that map peatbogs in High elevation environments. These studies were focused on much smaller areas (e.g., Villarroel et al. 2014) and were located at lower latitude Tropical Andes (e.g., Otto et al. 2011) where climatic variables differ from the present study. Our approach combines a well known, methodologically transparent and operationally easy classification process with a simple post-processing technique that improves the accuracy of map by 7 % in an important variable to this cover class (i.e., number of polygons) applied to a large region. This approach could be easily replicated to other large regions and at low cost for management and land use planning. The approach here developed can be easily applied, for example, in vast areas of the dry tropical and subtropical Andes (e.g., southern Perú, southwestern Bolivia, northern Chile), as well as areas in Asian highlands. Extrapolation to moister or more populated areas should be careful, however, in particular being aware that irrigated croplands and moist pasturelands may have similar spectral characteristics to peatbogs. A specific factor to be considered for successful classifications in each situation is the selection of images' date. In our case, we used rainy season (summer) images because high photosynthetic activity gives peatbogs a strong vegetation signal (e.g., high ndvi, low reflectance in the red, high in nir; Fig. 3d), and thus they become highly contrasting with the surrounding matrix where vegetation is much sparser and spectral signature is still largely controlled by bare soil. In contrast, during the dry season peatbog lost greenness increasing confusion with matrix. In addition to lower spectral differences between peatbog and no peatbog vegetation during the dry season, winter images showed many peatbogs frozen (i.e., with high "white" reflectance) particularly at higher elevation, which masked the vegetation and increased confusion with snow fields. Given that overall the study area is very dry, even during the "rainy" summer, we were able to obtain cloud-free images, a convenient situation that may not apply to other mountain ecosystems.

Our mapping procedure yielded a peatbogs' total cover of 94427.55 ha (0.66 % of total study area) distributed on 10,428 polygons (Table 1). This percentage is considerably smaller than other analyses in the same ecosystem type. For example, Boyle et al. (2004) reported that approximately 4 % in a study area of 254,000 Km^2 partially overlapping (NW) with our study area was covered by peatbogs but their classification had very few ground truth points for validation (only two GT for the peatbogs class). We showed through an extra validation process that our method is a conservative measure of peatbogs' area (Table 2), but the underestimation of the peatbogs area is in the order of 15–20 %. While at regional scale, our approach provided a reasonable description of geographic patterns; for more local decision management, this bias could be reduced by means of more intensive inclusion of control points.

A disproportionally large percent of peatbog area is included on few large peatbogs (Fig. 5). Due to their extent, these units may be particularly species rich. However, they are restricted to the lower altitudinal range in the northernmost portion of the study area, and the smaller and more isolated peatbogs probably include higher levels of endemism or biodiversity particularities, as well as an influence on a large number of watersheds, therefore having a potentially high conservation priority. Extreme aridity, intense solar radiation, high-speed winds, hypoxia, daily frost, and a short growing season contribute to put these isolated peatbogs at the ecophysiological limits of plant life (Squeo et al. 2006a) potentially highlighting their biodiversity conservation value as representative of extreme habitats.

Watersheds were grouped mostly on the basis of peatbogs cover, size, and isolation's (Fig. 7). Sub-watersheds with largest size and cover of peatbogs are associated to higher human population (i.e., *Abra Pampa*, *San Antonio de los Cobres*, *El Aguilar*, *Susques*; i.e., group 1, Fig. 7) (http://www.sig.indec.gov.ar/censo2010/); while sub-watersheds with smallest and more isolated peatbogs are at highest altitude and with high salinity resulting from a dryer environment (groups 4 and 5, Fig. 7). These watersheds are sparsely populated, experience traditional transhumant pastoralism in the summer, and in some cases they experience expanding mining activities. These activities, to some degree, conflict with each other, as well as with the conservation of peatbog's biodiversity, a very scarce key ecosystem of these areas. Ecological fragility and climate change

(Vuille et al. 2008) as well as the traditional land use dynamic, specially transhumant systems, make these sparsely covered watersheds particularly vulnerable, and these watersheds likely deserve priority conservation targeting. The variety of peatbog typologies here described, as well as their patterns characterizing different watersheds, is key factors to the land use zonation and management of this region in the face of ongoing environmental change and regional management processes.

High Andean peatbogs represent the highest biodiversity and productivity of high dry Puna, and provide essential ecosystems services to local inhabitants. Knowing its geographic and functional features is a key baseline information aimed to develop spatially explicit guidelines for sustainable use and conservation planning of these systems. This research provides comprehensive and detailed spatial framework for such initiatives in Argentina.

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