

Hotspots of Wetland Area Loss in Colombia

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Abstract Wetlands are among the most productive ecosystems on the planet and they are being subjected to heavy pressure by human activities. Changes in wetlands due to human impacts have increased, and it is estimated that half of the global wetland area has been lost during the last century. Documented cases of wetland transformation confirm the trend in Colombia. We used official nationwide wetland maps and land cover maps to quantify the areas within wetlands with non-natural land cover, such as pasture or cropland; and we used spatial analysis tools to identify the regions of the country where greater wetland transformations have occurred. Approximately 24 % of the area of mapped wetlands has land cover types related to intensive rural land use. Pastures and other types of land cover related to raising cattle account for 4 million ha and cover 50 % of the transformed wetland areas. There are 14 different regions where wetland loss is the most critical in Colombia. We analyzed the wetland areas related to raising cattle, agriculture, deforestation, and mining separately and found different spatial patterns for each activity. Hence, different conservation policies should be implemented across the country to account for spatial differences in the drivers of change.

Keywords Wetland loss · Hotspot · Wetland change · Change drivers · Colombia

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Introduction

A wetland is an ecosystem in which geomorphologic and hydrologic conditions cause saturation of the surface for a duration that is sufficient for the formation of hydric soils and conditions that are favorable for hydrophilic vegetation (Jackson et al. 2014). Wetlands are among the most productive ecosystems on the planet, support millions of people and provide important services, such as improving water quality, reducing flood damage, supporting high levels of biodiversity and secondary productivity, and providing wildlife habitat (Yuan and Zhang 2010). According to Jackson et al. (2014), wetlands are constantly changing due to their destruction, creation and movement to different locations. Almost all wetlands are recent from a geologic perspective (i.e., less than 12,000 years). Although some areas with large concentrations of wetland are ancient, such as the Amazon, the wetland features themselves are constantly shifting because of fluvial dynamics and other natural processes. The main drivers of natural wetland change are eutrophication, sedimentation, erosion, glaciation, climate change, water table level changes, and sea level changes (Yuan and Zhang 2010; Ross and Adam 2013; Jackson et al. 2014).

Human activities are also responsible for wetland losses around the world. Wetlands are under heavy pressure because many people think that they are of little economic value relative to other economic activities, and also because the society often does not recognize the services provided by wetlands at all (Turner et al. 2000; Scholte et al. 2016). Changes in wetlands due to human impacts have significantly increased during the last century (Ramachandra et al. 2005; Hussien Aragaw 2014). On a global scale, approximately half of the global wetland area was lost during the twentieth century (Zedler and Kercher 2005), which is a serious

environmental issue that has caused environmental sustainability concerns (Chen and Liu 2015).

The trend in Colombia is not different. National policies backed by the World Bank in the 1950s encouraged the transformation of wetlands to productive agricultural areas to foster economic development (Camargo 2012). Wetlands located in the floodplains of the Magdalena River Valley have been transformed to pastures for raising cattle (Márquez 2001; Garzón Yepes and Gutiérrez Camargo 2013), and wetlands in the Sinu River Valley have been drained to develop agriculture following 1960 (Camargo 2012). Furthermore, a loss of 88 % of wetland area between 1950 and 1980 was reported in the Cauca River Valley (Restrepo and Naranjo 1987; Beach and Luzzander-Beach 2012), and a reduction in the wetland area from 50,000 ha to 800 ha between 1950 and 2005 was reported for Bogota (Ramírez et al. 2013).

Wetland conservation and restoration policies should be based in comprehensive knowledge about changes in wetland extent and conditions. Li et al. (2015) stressed the existing need at national and international levels to report and monitor changes in wetlands for large areas using cost-effective tools. Assessing wetland change involves using data from the same area obtained on different dates to quantify changes in the landscape (Klemas 2013). This kind of analysis is mainly based on published land cover maps or remote sensing products. In this sense, a dense time-series of satellite images helps to distinguish between the ecosystem dynamics and other changes (Kayastha et al. 2012).

In Colombia, the study and creation of a wetland map at the national scale was triggered by the damages and losses caused by an extremely rainy period during late 2010 and early 2011. Extreme flooding affected more than 1,600,000 ha of the country's territory and caused economic losses to 7 % of the country's population (Cepal 2012). Knowledge regarding the locations and expansion of wetlands was needed to support environmental planning, land management and disaster prevention policies. The Humboldt Institute, with support from the national government through the National Environmental Information System and the Adaptation Fund, built a nationwide wetland map using the official information available for the country, with a scale of 1:100,000 for soils, geomorphology, land cover and flood frequency information, and later began studying wetland changes at the national scale.

An assessment of drivers of wetland change for a set of selected watersheds in Colombia was conducted in 2014 (Ricaurte et al. 2014). This study analyzed the human activities with the most negative impacts on wetlands, and a quantitative change analysis was conducted from the official land cover maps at a scale of 1:100,000 that were published in 2005 and 2010. The results of this work are very important regarding the analysis and mapping of the drivers of change; however, the change analysis approach has one drawback. The 2005 land cover map was obtained from a mosaic of

satellite imagery acquired between 2000 and 2002, and the 2010 land cover map was conducted from satellite imagery acquired between 2005 and 2009 (SIAC 2015). Several regions in the country have land cover data with a three-year time lapse, while other regions have data with time lapses of up to nine years. This difference in data acquisition dates and time lapses between maps can mask the changing magnitudes and trends and limits the analyzed time period to less than a decade.

In this work, we identify wetland areas that have lost their natural land cover by using the most recent countrywide wetland map (Humboldt Institute 2015) and the official 2010 land cover map of the country (IDEAM 2010), which are both at the 1:100,000 scale. We use spatial data processing and exploratory spatial data analysis tools (Anselin 1995, 2003) to answer the following questions: Where are the critical areas of wetland loss in the country? What activities are currently related with those areas? Results from this work will be helpful for understanding wetland change in the country and could be used to improve environmental management and policy making in Colombia.

The rest of this paper is organized as follows. Section 2 describes the data and methods. The results of the analysis are presented in Section 3. Section 4 shows a discussion of the results, and the conclusions are presented in Section 5.

Methods

The most frequently used quantitative indicators of wetland change are measures of wetland area within the landscape and the percentage of wetland area from two different dates. Wetland loss is usually measured as the wetland area or percentage of wetland area that was transformed to a different type of land cover during the time lapse between analyses (Song et al. 2011; Yu et al. 2011; Jiang et al. 2012; Ottinger et al. 2013). Because the time lapse between the available official land cover maps varies and is shorter than a decade, we quantified wetland loss as the area of mapped wetlands with land cover types associated with human intervention, such as crops (agriculture) or pastures (cattle raising), rather than natural types of land cover in the land cover map of 2010.

Study Area

Colombia is located in the northwestern corner of South America and covers approximately 1,142,000 Km². The country is characterized by a tropical climate with high precipitation and fluvial discharge ranging from 100 mm per year at the Caribbean to over 6000 mm per year at the Pacific (Rodríguez et al. 2015). From south to north, Colombia is transected by the Andean Mountain System, which reaches

an elevation of 5000 m.a.s.l. A large part of the country consists of plains and low lands that extend towards Venezuela, Brazil and the Caribbean. The population density of the country is 43.55 people/Km² (2014 data, <http://data.worldbank.org/indicator/EN.POP.DNST>). The population is unevenly distributed, with more than 76 % of the population located in urban areas. Most towns and cities are located in the Andean region and on the Caribbean Coast (3500 people/Km²), and the population density is less than 1 person/Km² in the southern and western parts of the country (<http://www.dane.gov.co>). The main drivers of landscape change in the country have been population expansion and intense human activities (Rodríguez Eraso et al., 2013). According to Rodríguez et al. (2015), more than one-third of the territory has been transformed, with agriculture and cattle raising as predominant land uses in the Andes and on the Caribbean Coast. Tropical humid forests are still present towards the east in the Amazon River Basin and towards the west on the Pacific Coast, and savannahs exist in the Orinoco River Basin towards its boundary with Venezuela.

Data

We used the 1:100,000-scale national wetland map (Humboldt Institute 2015) to extract wetland boundaries. This map identified wetland areas throughout the country using different types of spatial data at the 1:100,000 scale, including hydrography data from topographic maps (IGAC 2014a), geomorphology and hydric soils data (IGAC 2014b), vegetation and land cover data (IDEAM 2010, 2012), and flood frequency data between 2007 and 2011 (IDEAM, SARVISION, & I. Humboldt 2014).

Each information layer was analyzed by experts to identify what units were associated with wetlands. Water bodies and rivers were extracted from hydrography data. Landforms that allow water accumulation such as basins and flood plains were selected as well as soils groups that keep evidence of inter or intra annual flooding. Vegetation data was also used: swamp forest, mangroves, and flooded grasslands, among other classes from land cover maps were incorporated. Finally, all data layers were integrated with the flood frequency map. The first map version was reviewed in eight workshops with 87 experts from regional environmental agencies and national natural parks. The map was adjusted and validated statistically after the workshops.

The Colombian wetlands map's has a thematic accuracy of 75.79 %. This was calculated through a stratified random sampling. A total of 3179 points were assessed in 19 windows that occupied 16 % of the country inland territory. The windows corresponded to the Colombian watersheds. Their selection was based on three criteria: different wetlands types representation, availability of satellite imagery and area covered. Taking into account each watershed size, the number of points

were estimated within a 95 % confidence interval following Chuvieco (1995), McCoy (2005) and Meidinger (2003). The details of the Colombian wetlands maps are explained in Flórez et al. (2016, *in press*). The map identified five wetland classes: open permanent wetlands, forested permanent wetlands, temporal wetlands, areas with medium potential of being wetlands and areas with low potential of being wetlands (Fig. 1).

We used the official 1:100,000-scale national land cover map (IDEAM 2010, 2012) to quantify the area of each land cover class within the wetlands and to identify the areas with transformed land cover. This map was built based on an adaptation of the Corine Land Cover Methodology for Colombia and was based on the interpretation of Landsat and SPOT images with field validation.

We created a regular grid of square cells with a cell size of 10 Km over the inland territory of the country to quantify wetland loss. We used this grid to map the magnitude of wetland change in an objective manner without administrative boundaries. For each cell, we quantified the wetland area, the area of natural and transformed land cover classes within the wetlands, and the percentage of area within the wetland cell with transformed land cover classes.

Quantification of Wetland Area Loss

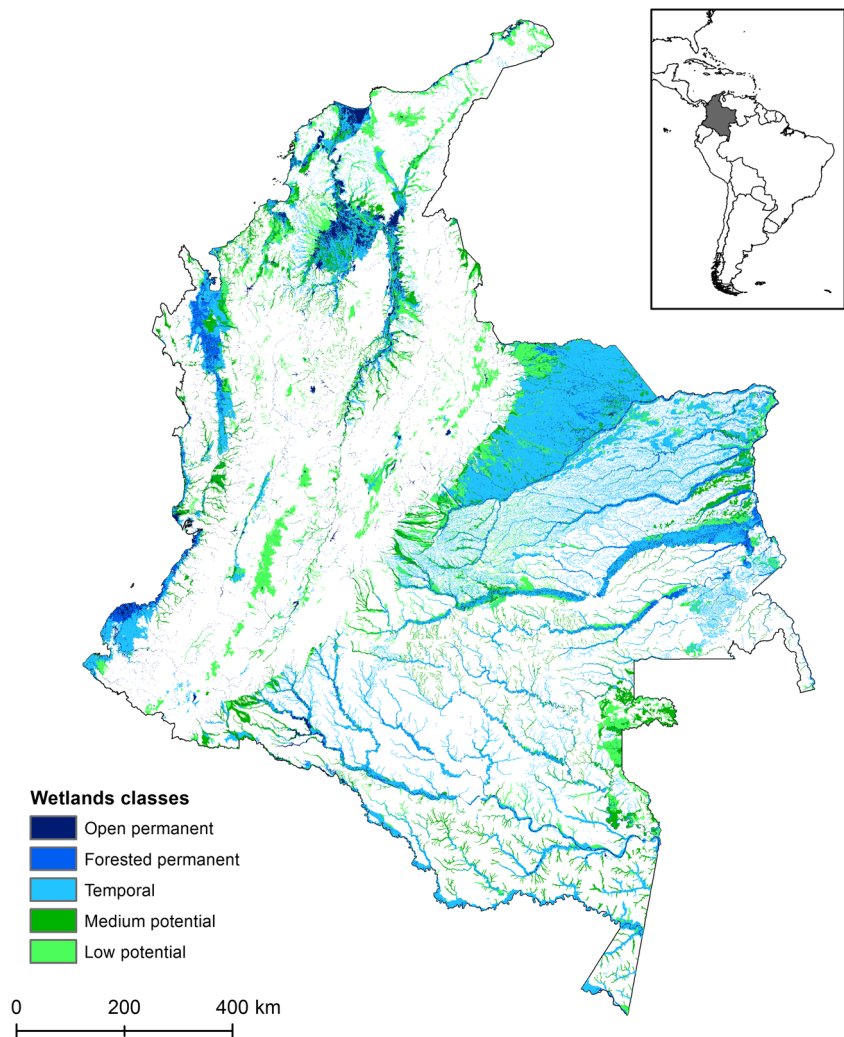
We quantified wetland loss by intersecting the wetland map layer with the land cover map layer in a GIS. The wetland map was built in raster format with a cell size of 25 m. We changed the format of this map to polygons and then intersected it with the land cover map. The result of the intersection was edited to only select the non-natural land cover classes associated with induced transformation (Table 1), which we assumed was equal to the wetland loss area. The total area of these land cover classes was added in each cell in the regular grid. Then, we calculated the percentage of wetland loss area within each cell and ran a hotspot analysis using this variable.

Identification of Hotspots of Wetland Area Loss

We used three different techniques for hotspot identification: (1) heat maps with kernel density estimation (Rosenblatt 1956; Parzen 1962), (2) spatial clusters of significantly high values using a local indicator of spatial association (LISA): the local Moran's I (Anselin 1995), and (3) spatial clusters with significant high values according to the Gi statistic (Getis and Ord 1992).

The heat map allows for the rapid identification of hotspots by weighting the value of an interest variable within a moving window that moves across the entire study area. We built this map using QGIS (QGIS Development Team 2015) with the Heat Map plug-in using the centroids of the regular grid as

Fig. 1 Colombian wetlands map (Humboldt Institute, 2015)



input and weighting the value of the percentage of wetland loss area in each cell over a kernel radius of 50 Km.

According to Anselin (1995), the hotspots of a variable can be identified from the areas where LISA is significant. The LISA cluster map shows the areas with atypically high values or atypically low values of the phenomena with statistically significant values of LISA. We built this map using the Univariate local Moran's I function in GeoDa software with 999 permutations (Anselin et al. 2006), and we processed the map to only show the areas with clusters of high values surrounded by other high values, which correspond to the areas with higher incidence of wetland loss.

The general Gi statistic of Getis and Ord (1992) is similar in meaning to the LISA indicator because it checks the null hypothesis that no clustering of high or low values occurs. When this statistic is significant, spatial clusters of atypically high or low values exist. We built the Gi cluster map using the Local G Statistics Maps function in the GeoDa software and then processed it to only show the clusters of high values.

We used kernel density estimation to build heat maps separately for the most important activities related to wetland area loss: cattle raising, deforestation, and agriculture. In addition, a mining heat map was produced. Although this activity has a low impact on the loss of wetland area, it has a significant and high impact on other aspects, such as water quality.

Results

Table 2 shows the wetland area loss across the country and the current land uses in the area. More than 7 million ha of wetlands have land cover types related to human activities, which correspond to approximately 24 % of the mapped wetland area in the country. The human activities mainly responsible for wetland loss in Colombia are cattle raising, agriculture and deforestation, which together account for nearly 95 % of the loss of wetland area in Colombia. Burned land and other types

Table 1 Land cover classes related to human activities

Land cover class, codes and description	Related human activity
1.1.1. Continuous urban fabric	urbanization
1.1.2. Discontinuous urban fabric	urbanization
1.2.1. Industrial and commercial land	urbanization
1.2.2. Road network, rail network and related land	infrastructure
1.2.3. Seaport land	infrastructure
1.2.4. Airports	infrastructure
1.2.5. Waterworks	infrastructure
1.3.1. Mining	mining
1.3.1.2. Oil mining	mining
1.3.1.6. Salt mining	mining
1.4.1. Green urban areas	urbanization
1.4.2. Recreational facilities	urbanization
2.1.1. Other seasonal crops	agriculture
2.1.2.1. Rice	agriculture
2.1.2.2. Corn	agriculture
2.1.3.1. Cotton	agriculture
2.1.4.1. Onion	agriculture
2.1.4.2. Carrot	agriculture
2.1.5.1. Potato	agriculture
2.2.1.1. Other permanent arable crops	agriculture
2.2.1.2. Cane	agriculture
2.2.1.2.1. Sugarcane	agriculture
2.2.1.3. Plantain and banana	agriculture
2.2.2.1. Other permanent bush crops	agriculture
2.2.2.2. Coffee	agriculture
2.2.2.3. Cocoa	agriculture
2.2.3.1. Other permanent tree crops	agriculture
2.2.3.2. Oil palm	agriculture
2.2.4. Agroforestry crops	agriculture
2.2.5. Confined crops	agriculture
2.3.1. Clean pasture	cattle raising
2.3.2. Wooded pasture	cattle raising
2.3.3. Weedy pasture	cattle raising
2.4.1. Crop mosaic	agriculture
2.4.2. Pasture and crop mosaic	cattle raising
2.4.3. Crop, pasture and natural spaces mosaic	cattle raising
2.4.4. Pasture and natural spaces mosaic	cattle raising
2.4.5. Crop and natural spaces mosaic	agriculture
3.1.3. Fragmented forest	deforestation
3.1.3.1. Fragmented forest with pastures and crops	deforestation
3.1.3.2. Fragmented forest with secondary vegetation	deforestation
3.1.5. Forest plantation	forestry
3.1.5.2. Broadleaf plantation	forestry
3.2.3. Secondary vegetation	deforestation
3.2.3.1. High secondary vegetation	deforestation
3.2.3.2. Low secondary vegetation	deforestation
3.3.3. Bare and degraded land	deforestation
3.3.4. Burned land	burned land

Table 2 Area of wetland loss and human activities in Colombia

Activity	Wetland loss (ha)	Wetland loss (%)
Cattle raising	4,667,716.4	63.7
Deforestation	1,168,108.3	15.9
Agriculture	1,119,153.6	15.3
Burned land	170,555.1	2.3
Urbanization	164,205.6	2.2
Mining	20,861.4	0.3
Forestry	14,232.0	0.2
Infrastructure	7824.0	0.1
Total	7,332,656.4	100

of land cover related to urbanization, mining, forestry, and infrastructure account for 5 % of wetland loss.

Figure 2 shows the results of the hotspot identification analysis obtained using the three methods: kernel density, Local Moran's I, and the Gi statistic. The differences among the results from the different methods are minimal, with very high agreement and pointing to the same hotspot areas of wetland loss. In addition, the kernel density results show differences between the magnitudes of the identified zones and allow for more detailed delimitation of the hotspots. In general, wetland loss has affected lowlands (less than 1000 m.a.s.l.), with the exception of one area: the high plains of Bogota (2600 m.a.s.l.) that extend north from Bogota City in the Andean zone.

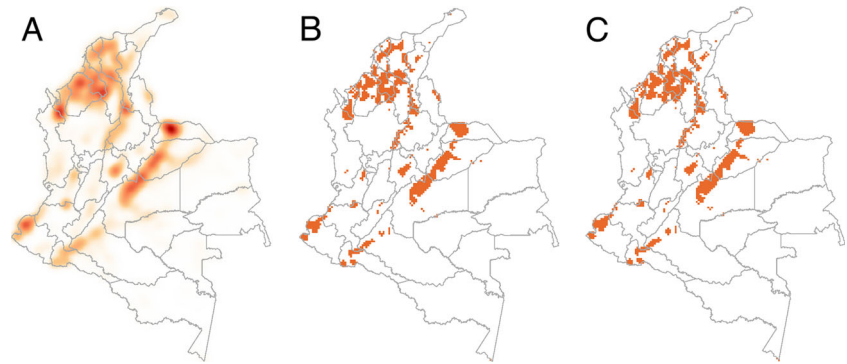
According to these results, at least 14 hotspots of wetland loss can be identified across the country. All hotspot areas are located near the Andean zone and towards the Caribbean Coast, which are areas with higher population densities. Figure 3 shows the hotspots of wetland loss over the department boundaries, which are the top level of administrative boundaries in Colombia.

Figure 4 shows the hotspots of wetland loss due to cattle raising, deforestation, agriculture and mining. Although each activity exposes a different spatial pattern, it was observed that areas of deforestation correspond with areas used for cattle raising or agriculture. Otherwise, mining follows an independent pattern.

Discussion

This analysis focuses on wetland area loss, which is one aspect of wetland change. Other important aspects of wetland change, such as loss of biodiversity, loss of connectivity, sedimentation processes, or decreases in water quality, are beyond the scope of this analysis. Nevertheless, the wetland area loss could be used as an objective quantitative indicator for evidence-based policy making and monitoring when it is

Fig. 2 Hotspots of wetland loss in Colombia identified using three different methods: kernel density (a), Local Moran's I (b), and Gi statistic (c)



complemented with further information such as authorized land use and accessibility data (Clare and Creed 2013).

The information used for this analysis presents some limitations regarding thematic and positional accuracy. However, this information is the best information currently available and was generated using proven methods in a scientific and objective way. The wetland area loss data presented in this work can be considered as the best estimates that are available for the entire country. These data are objective, not skewed towards

particular interests and allow general insights regarding the transformation of wetlands in the country and the related human activities.

Approximately 24 % of the total wetland area in Colombia has been lost. The main activities in these areas are related to intensive land use in rural areas, including cattle raising, deforestation, and agriculture. This result agrees with the main drivers of wetland area changes in other countries around the world (Rebello

Fig. 3 Hotspots of wetland area loss over administrative boundaries

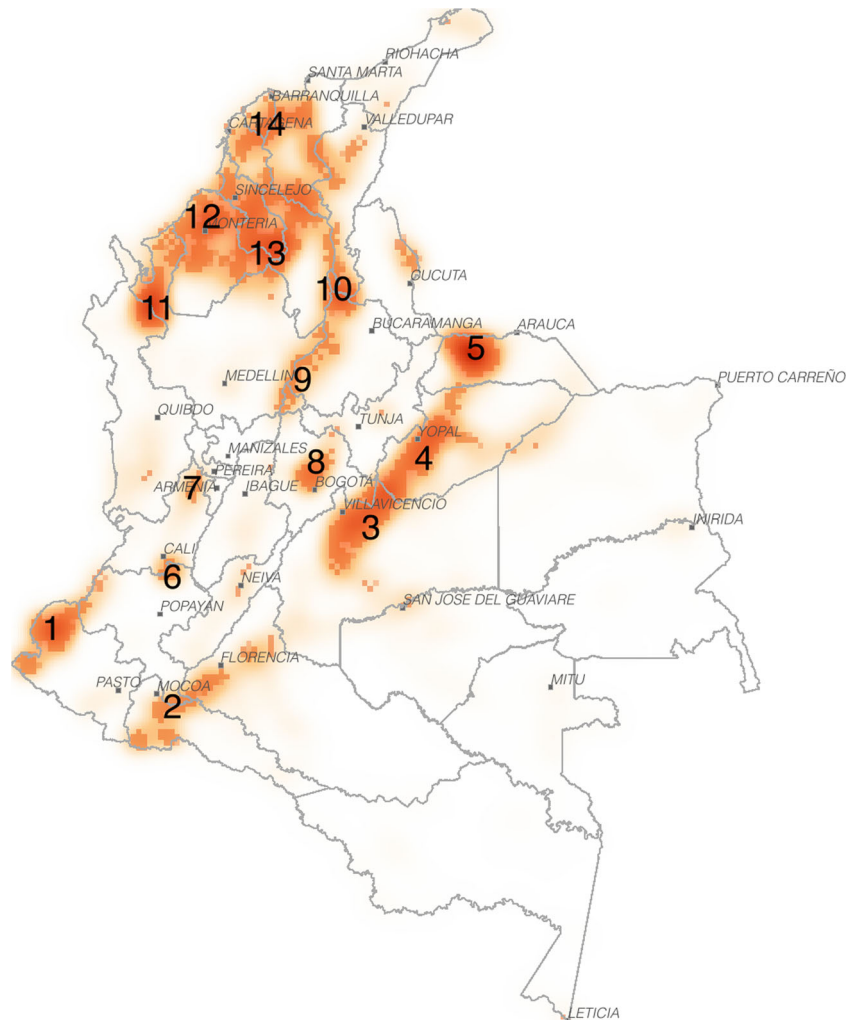
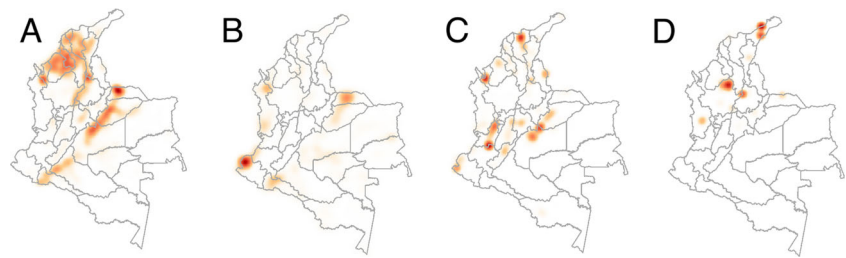


Fig. 4 Hotspots of wetland area loss related to different activities: cattle raising (a), deforestation (b), agriculture (c), and mining (d)



et al. 2009; Niu et al. 2012; Rodríguez Eraso et al. 2013). However, we highlight that the Colombian case is mainly driven by cattle raising, which accounts for more than 50 % of the wetland loss and for the conversion of more than 4 million ha of land to pastures.

According to Camargo (2012), wetlands were historically regarded as wastelands and obstacles to economic development. The International Bank for Reconstruction and Development, IBRD (today the World Bank), sent an economic Mission in 1949 to explore the Colombian territory and concluded that the country had great potential for large-scale agriculture development; however, flooding and wetland areas were considered as major obstacles (Currie 1950). Based on this view, the Colombian government contracted an American engineering consulting firm to develop a plan for flood control and water management in areas with high potential for agricultural expansion, and the IBRD mission proposed draining wetland areas to expand agriculture based on that plan (Camargo 2012).

Deforestation is particularly important in the western zone of the country, where tropical humid forests are being illegally exploited or replaced by plantain and banana crops, or palm plantations. These areas were also highlighted in the Forest to No-Forest report by the IDEAM based on forest-change maps from 1990 to 2000 and 2000–2005 (Cabrera et al. 2011). In the same sense, deforestation is considered a main driver of land use change and is commonly followed by agriculture and cattle raising land use. When soils are fertile, agriculture remains the dominant land use; otherwise, the land is used for livestock in the future.

The hotspots of wetland loss are mainly located near the Andean zone in the Magdalena and Cauca River Valleys, toward the plain lowlands in the east, and towards the Caribbean Coast in the north. There is also one identified hotspot on the Pacific Coast in the south. These results share the same spatial pattern of forest conversion and land use assessment reported by Etter et al. (2006), which indicates that different ecosystems exhibit similar transformation patterns. With the exception of the Pacific coast hotspot, the regions mentioned above are characterized for having high population densities and high urbanization.

Towards the east, the Amazon and Orinoco Basins have the lowest values of wetland loss. The population densities in these areas are the lowest in the country. In addition, the lack

of road infrastructure in this area could have shielded these areas from negative human impacts.

In general, the individual activity maps exhibit different patterns. Nevertheless, the deforestation map shows a relationship between cattle raising and agriculture hotspots. This relationship is consistent and was explained above. Although mining is not one of the main activities related to wetlands loss, an individual map was produced to show the high impacts of mining on the supply of water for human consumption. The areas in the center of Colombia are vulnerable to water pollution, and the water bodies and streams in these areas are important for crop irrigation, fish production, and the supply of drinking water. In the north, mining impacts the soil structure as well as water infiltration and aquifers recharge. This area is the driest area in Colombia, with inadequate aqueduct and sewage infrastructure where people depend on the water provided by the aquifers.

Thus, the hotspot maps showing the lost wetland area related to different processes or activities (Fig. 3) indicate different hotspots across the country and show different spatial patterns. These maps are very important because they indicate that using one single wetland conservation policy throughout a country is inadequate. The regions most affected by cattle raising are different from the regions affected by agriculture, deforestation, and mining. A smart policy for wetland conservation requires acknowledging these differences throughout the territory and should propose different actions for different locations.

Furthermore, information regarding land-use activities and wetlands types at the regional scale can be used to understand ecosystem change triggers and trends and lead to more adequate decision making and planning. In addition, continuous data and the implementation of a wetland monitoring program will improve management programs that aim to preserve these ecosystems and their services and could be used to identify new risk management strategies, which is one priority of the Colombian government.

Conclusions

Intensive land use occurs in most areas where wetlands have been lost in Colombia. This result is partially an outcome of an outdated view of development in which wetland ecosystems

were considered as mosquito breeding-areas and as a source of new land for urban or rural development. Quantifying the area of wetlands converted to intensive land use provides an indicator of the magnitude of landscape changes encouraged by this political vision. Now that the importance of wetland ecosystems is more recognized, the use of analytical tools provides a method for estimating the impacts of those policies and identifying the locations that are most affected. Maps of wetland area loss provide a powerful tool for making informed decisions and show the areas of the country that require more attention when proposing policies and actions to reverse trends of wetland loss.

The maps of hotspots of wetland area loss related to cattle raising, agriculture, deforestation, and mining all show different spatial patterns that point toward different locations across the country. These results are simple yet powerful and indicate that the country should use a set of different policies that consider the differences in the drivers of change across the territory, as well as the differences in the types of wetlands affected.

Although our outcomes have a national scope, they can be complemented with detailed information of land use and wetland ecosystems at the regional or local scales. This information will allow stakeholders and local environment agencies to propose different wetland management strategies for different regions.

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