MONITORING ACTIVE FIRES IN THE LOWER PARANÁ RIVER FLOODPLAIN: ANALYSIS AND REPRODUCIBLE REPORTS ON SATELLITE THERMAL HOTSPOTS

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ABSTRACT:

Floodplain wetlands play a key role in hydrological and biogeochemical cycles and comprise a large part of the world's biodiversity and resources. The exploitation of remote sensing data can substantially contribute to monitoring procedures at broad ecological scales. In 2020, the Lower Paraná River floodplain (also known as Paraná River Delta, Argentina) suffered from a severe drought, and extended areas were burned. To monitor the wildfire situation, satellite products provided by FIRMS-NASA were used. These thermal hotspots —associated with active fires— can be downloaded as zipped spatial objects (point shapefiles) and include recent and archive records from VIRRS and MODIS thermal infrared sensors. The main aim was to handle these data, analyze the number of hotspots during 2020, and compare the disaster with previous years' situation. Using a reproducible workflow was crucial to ingest the zip files and repeat the same series of plots and analyses when necessary. Obtaining updated reports allowed me to quickly respond to peers, technicians, and journalists about the evolving fire situation. A total of 39,821 VIIRS S-NPP thermal hotspots were detected, with August (winter) accounting for 39.8% of the whole year's hotspots. MODIS hotspots have lower spatial resolution than VIIRS, so the cumulative MODIS hotspots recorded during 2020 were 8,673, the highest number of hotspots of the last 11 years. Scripts were written in R language and are shared under a CC BY 4.0 license. QGIS was also used to generate a high-quality animation. The workflow can be used in other study areas.

1. INTRODUCTION

Wetland ecosystems play a key role in hydrological and biogeochemical cycles and comprise a large part of the world's biodiversity and resources (Keddy, 2010). South America is the continent with the largest surface covered by wetlands, with the greatest extension being covered by fluvial wetlands associated with the Amazonas, the Orinoco and the Paraguay-Paraná rivers (Junk et al., 2013). These ecosystems' dynamics are mainly controlled by flood pulses (Junk et al., 1989), which determine fluxes of materials and organisms between the river and the floodplain, influence ecological processes, and affect biodiversity patterns (Gayol et al., 2019; Marchetti and Aceñolaza, 2012; Morandeira and Kandus, 2017).

Due to the large extension of fluvial wetlands and their restricted accessibility, the exploitation of remote sensing data can substantially contribute to monitoring procedures at broad ecological scales (Kandus et al., 2018; Tiner et al., 2015). This is especially true during extreme events that limit accessibility even more than usual, such as floods, droughts (hindering navigation), or wildfires. In 2020, the Lower Paraná River floodplain (also known as Paraná River Delta, Argentina) suffered from a severe drought, and extended areas were burned. These wildfires had high environmental impacts and affected the health of the population living in the islands and in the close high-density cities (Verzeñassi et al., 2020). Besides environmental conditions, lockdown due to the epidemiological situation was an extra factor limiting accessibility.

The use of remote sensing data in fire monitoring and management involves several data types and methods, depending on the objective: alert on fire danger conditions, detect active fires and burned areas, analyze fire effects and vegetation recovery, etc.; and has been applied in ecosystems around the world. Active fire detection relies on the infrared thermal signal: high thermal contrast between hotspots and the surrounding pixels in the middle-infrared region (3-5 µm) (Chuvieco et al., 2020).

Fire hotspot products derived from satellite systems are shared within ca. 3 hours of satellite observation by the Fire Information for Resource Management System (FIRMS-NASA) and can be freely accessed with an open sharing data policy. Two main types of products are available in the FIRMS-NASA database, differing in their spatial resolution and historic coverage. VIIRS products from S-NPP and NOAA-20 satellites are available since 2012 and 2017, respectively, and are derived from 375 m pixel resolution images (NASA's Fire Information for Resource Management System, 2021a). This operational product has the best compromise between spatial and temporal resolution (Chuvieco et al., 2020). Besides, hotspot products derived of 1 km pixel images from Terra & Aqua MODIS satellites are available since November 2001 (NASA's Fire Information for Resource Management System, 2021b), allowing comparisons with previous periods.

The aim was to handle these spatial data on active fires in the Lower Paraná River floodplain and to analyze and report the number of hotspots during 2020. A comparison with previous years' situation was also addressed (*e.g.*, fires occurring in 2008

(Kandus et al., 2009; Salvia et al., 2012)). Since the 2020 fires occurred for several months (mainly June to November), using a reproducible workflow was crucial to ingest the zip files and repeat the same series of plots and analyses when necessary. Open geospatial software was used in all the processing steps, mainly R (R Core Team, 2020) and QGIS (QGIS Development Team, 2020). Obtaining reproducible reports was crucial because of the evolving wildfire situation, so RMarkdown was used (Xie et al., 2018).

2. METHODS

2.1 Study area

The case study area was the Lower Paraná River floodplain (Paraná River Delta), which runs 400 km South-Southeast along Argentina's main populated and industrial area and covers 19,300 km^2 (Figure 1) (Kandus et al., 2019). In this zone, the floodplain reaches 10 to 30 km wide. Shallow lakes and emergent macrophytes dominate (Borro et al., 2014; Morandeira and Kandus, 2015). The climate is temperate humid; the mean annual temperature is 17.1 °C, January being the hottest month and July the coldest (24.0 °C and 10.3 °C, respectively). Mean annual precipitation is 1074 mm, March being the wettest month and August the driest (126.4 mm and 42.1 mm, respectively) (1965-2019, Instituto Nacional de Tecnología Agropecuaria at 33°44'S 59°41'W).

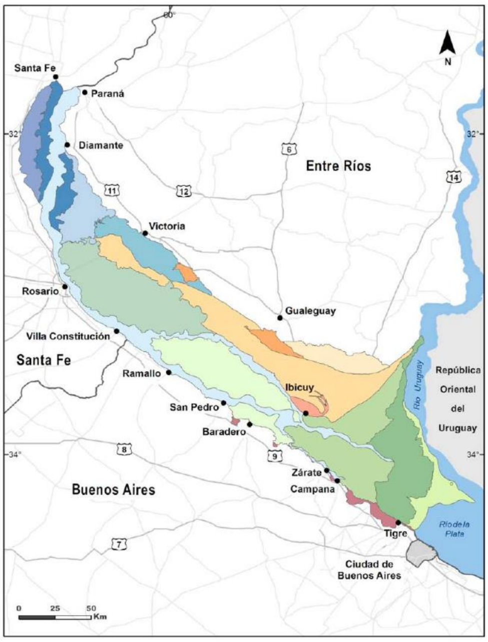

Figure 1. Case study area: Lower Paraná River floodplain in Argentina. Reproduced with permission from Kandus et al. 2019. In the map, colors indicate different Landscape Units (see Kandus *op. cit.* book for details).

In 2020, a severe drought occurred and Paraná River water levels were the lowest since 1971 (Juan Borús – Instituto Nacional del Agua, *com. pers.*). These hydroclimatic conditions favored the propagation of fires, 95% of which were initiated by humans (intentionally or accidentally), according to the Argentinian National Environmental Minister.

To run the R script, only a polygon of the study area (e.g., shapefile or geopackage) is needed. However, ancillary information is useful to understand the ecological situation. Several geographic data, as well as expert knowledge of the author and collaborators, were available to interpret which areas were being burned and the possible environmental impacts. Also, ground-truth information was available through local settlers, journalists and fire brigade members.

2.2 Active fire data acquisition

FIRMS-NASA products were periodically accessed and downloaded. The used product types were Near Real Time VIIRS (375 m resolution) from S-NPP satellite (NASA's Fire Information for Resource Management System, 2021a) to monitor active fires, and MODIS (1 km resolution) data (NASA's Fire Information for Resource Management System, 2021b) to analyze the fire history. These data are available as zipped spatial objects (point shapefiles). In order to do this non-automatable step as quickly as possible, a rectangular bounding box was drawn (with no need to be precise in the interest area), and all the available period was downloaded (November 2001 – present).

2.3 R workflow

The main workflow was written in R (R Core Team, 2020): from the zipped FIRMS data, the script generates plots and summarizes the obtained information. This R workflow can be used in other regions by changing the study area polygon input. Processing conducted on R accounts for these tasks:

a) *File ingestion and geometric operations*

1. Reading zip files in a given folder.
2. Unzipping the data.
3. Reading the hotspot point shapefiles and creating spatial objects. String patterns were looked for in the name files (*str_detect* function) to create meaningful hotspot objects. A study area polygon shapefile was also read.
4. Merging the hotspot spatial objects.
5. Reprojection of the hotspot objects to POSGAR 2007 / Argentina Zone 5 (EPSG 5347).
6. Clipping the hotspot data with the study area polygon.
7. Plot an interactive map of the 2020 VIIRS hotspots.
8. Exporting hotspot objects to geopackages.

b) *Data tidying and plots*

9. Data cleaning and tidying operations on attribute tables.
10. Select the 2020 VIIRS hotspots, compute the daily and the cumulative number of hotspots.
11. Plots (English and Spanish versions): Daily hotspots; Cumulative hotspots. Export png versions.
12. Compute the number of VIIRS hotspots per month. Plot and export. Report the month with the highest proportion of potential active fires.
13. Annual comparison: VIIRS and MODIS number of active fire records per year. Plot and export.
14. Generate html and/or pdf reports: English and Spanish versions.

As an alternative to steps 1-6, a QGIS model that can efficiently handle the same spatial operations was constructed. The R workflow is preferred because it avoids manually loading and selecting the layers: the user only needs to save the zip files in a given project folder.

The used R packages are sf (Pebesma, 2018), tmap (Tennekes, 2018), tidyverse (Wickham et al., 2019), janitor (Firke, 2021), stringr (Wickham, 2019), spdplyr (Sumner, 2020), ggplot2 (Wickham, 2016), and rmarkdown (Xie et al., 2018). The workflow and report scripts were published in a public github repository (bilingual: Spanish/English, see Appendix). Plots were published in the same repository (in the Readme.md) and shared in social networks and with peers and journalists when requested.

2.4 QGIS Animation

QGIS 3.14 (QGIS Development Team, 2020) was used to visualize the spatial data exported with R, along with ancillary geographic data, and further interpret which wetland types were affected. Also, a visually attractive animation of the hotspots was produced and was included in dissemination articles and talks. Although the plugin "Time Manager" was needed when the first animation was generated, now QGIS includes an integrated temporal control function (Graser, 2020). Frames generated in QGIS were converted to a gif animation using the Unix Shell "convert" command.

3. RESULTS

3.1 Active fires in the Lower Paraná River floodplain

An animated map of the potential active fires is available here https://github.com/nmorandeira/Fires_ParanaRiverDelta/blob/master/output/Morandeira2021_ParanaRiverDelta_Fires2020_animation.gif. In 2020, a total of 39,821 VIIRS S-NPP hotspots were detected (Figure 2), with August (winter in the Southern Hemisphere) accounting for 39.8% of the year's hotspots.

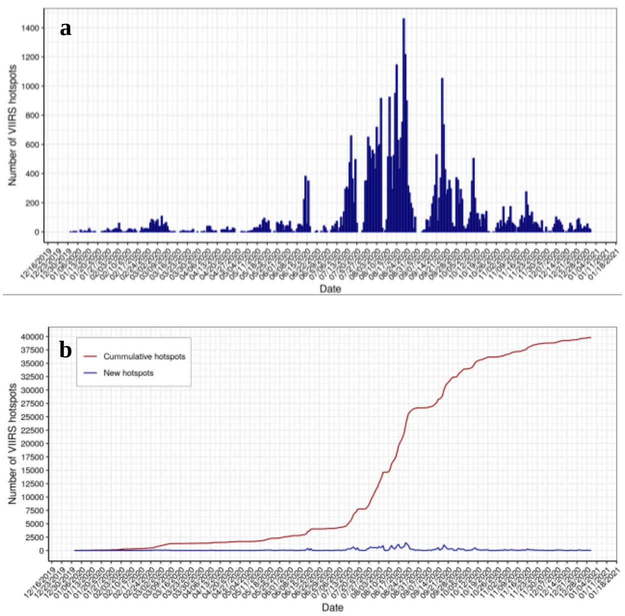

Figure 2. Thermal hotspots recorded during 2020, indicating potential active fires at the Lower Paraná River floodplain. Based on VIIRS S-NPP data (375 m resolution) from FIRMS-NASA. **(a)** Daily records; **(b)** Cumulative and daily records.

Historical fire activity from both VIIRS and MODIS sensors is shown in Figure 3. The cumulative MODIS hotspots recorded during 2020 were 8,673, the highest number of hotspots of the last 11 years. MODIS hotspots detected in 2020 were 62.9% of those recorded during 2008. While VIIRS data are available from 2012, MODIS data are available from 2001. MODIS hotspots have lower spatial resolution than VIIRS (pixel size: 1 km versus 375 m), so fewer hotspots are reported and each hotspot corresponds to a greater area (Figure 4).

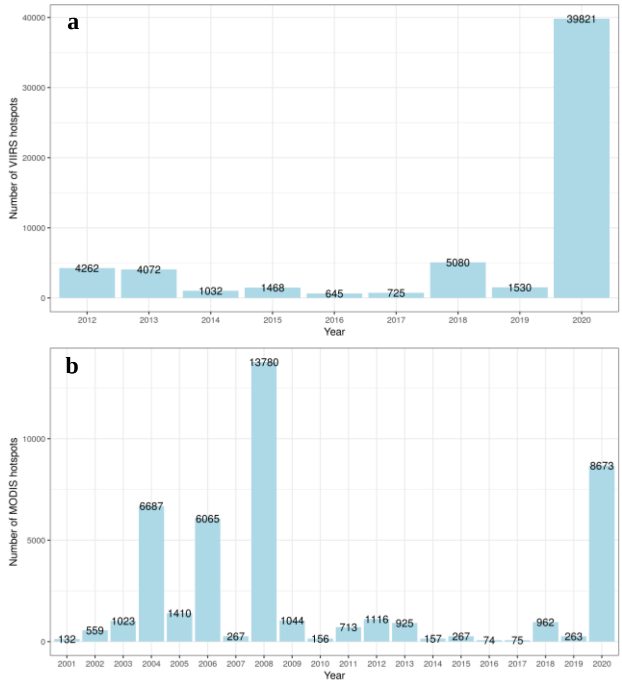

Figure 3. Historical fire activity: annual thermal hotspot records. **(a)** VIIRS S-NPP data (375 m resolution, 2012-2020); **(b)** MODIS (1 km resolution, November 2001-2020). Data obtained from FIRMS-NASA.\

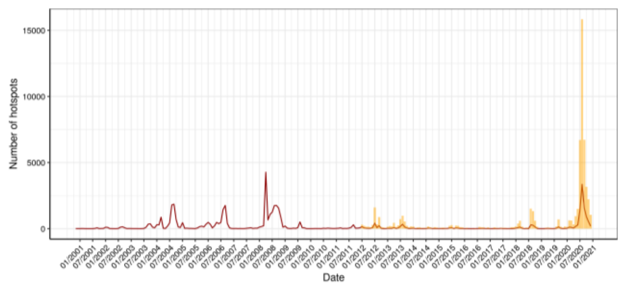

Figure 4. Historical fire activity: monthly records and comparison between sensors differing in their spatial resolution. Lines indicate MODIS hotspots (1 km, 2001-2020) and bars indicate VIIRS hotspots (375 m, 2012-2020).

3.2 Performance of the R workflow

All the plots and information summarized in Section 3.1 (except for the animation) were produced with the R workflow –plots in the report include title and subtitle, and a footnote with author attribution. When run in a 16 GB Intel-Core i7 laptop, an

English (or Spanish) html or pdf report with the plots here summarized is obtained in 1:18 minutes. Including an interactive map on the rendered html adds 30 seconds to the processing time.

4. DISCUSSION

The open-source workflow here presented facilitated monitoring and reporting fire activity in the Lower Paraná River floodplain during the 2020 lockdown. Using satellite thermal hotspot products allows to detect the potential active fires (Chuvieco et al., 2020), but can lead to underestimations or overestimations. Although ground-truth data are not shown in this article, the author has confirmed active fire locations with: a) information of local population and fire brigade members; b) georeferenced photographs obtained by López Brach during a flight over on-fire areas in June 2020 and gently shared to the author; c) post-fire visits done by the author in March 2021: charcoal and burned soils and vegetation were observed in sites that had been previously identified with thermal hotspot records.

The next step is to estimate burned areas from active fire monitoring: *i.e.*, to derive which wetland extensions were effectively burned (a polygon or multi-polygon product). Visual interpretation and digitizing in QGIS, aided by the hotspot data, can be done on an RGB composition or, alternatively, using a Normalized Burn Ratio (NBR) image (Harris et al., 2011). This synthetic index is the normalized difference between the near-infrared and the short-wave infrared channels. The NBR index can be derived from available optical scenes such as Sentinel-2 or Landsat 8-OLI. Current work is being done on automatizing the generation of burned area products by using the point hotspots and post-fire NBR images obtained from Sentinel-2 scenes. To account for this objective, a seeded region growing algorithm from SAGA (Bechtel et al., 2008) is run in R using the RSAGA library (Brenning et al., 2018). Including the SAGA module in an R script allows the user to test the algorithm's sensitivity to its main parameters: variance in the feature space, variance in the position space, and similarity threshold. This work is in progress.

Preliminary analyses of the distribution of hotspot records on ancillary geographic data (*e.g.* wetland inventory maps in Kandus et al. 2019) suggest that most of the burned wetlands belonged to herbaceous vegetation, such as marshes and macrophytes surrounding the shallow lakes, as well as sediments and roots that were exposed when shallow lakes dried. Field data on the impacts of these fires have not been analyzed yet, although the environmental impacts and the effects on public health were discussed last year (Kandus et al., 2020; Verzeñassi et al., 2020).

In 2008, extended fires in the Paraná River floodplain also occurred during a dry period (the drought was not as severe as in 2020). Although MODIS hotspots detected in 2020 were less than in 2008, burned area estimations by the Argentinean Environmental Minister show an inverse pattern. In 2008, 206,955 ha were burned, mainly corresponding to bulrush marshes (Stamati et al., 2008). In 2020, at least 328,995 ha had been burned by September (14,3% of the total study area, 52% belonging to natural protected areas) (Ministerio de Ambiente y Desarrollo Sostenible de Argentina, 2020). Fires continued in October-December, although most of the burned areas were affected during the Fall-Winter season.

By comparing the historical monthly MODIS peaks (Figure 4), it can be noted a bimodal distribution of the hotspot records in 2008 and a unimodal distribution in 2020. The spatial distribution of the fires also differed (comparing results of this work with those reported by Stamati et al. 2008). The low resolution of MODIS data and the fact that hotspots are not spatially independent (a hot pixel can be flagged on two consecutive dates) highlight the importance of accompanying this information with burned areas estimations (Chuvieco et al., 2020; Szpakowski and Jensen, 2019). Also, burn severity is important: a low severity fire –detected as a hotspot– may leave standing biomass that can be burned in a second fire event –leading to a second hotspot record–.

Burn severity is relevant for addressing environmental impacts, such as soil burning and alteration of soil nutrient composition, seed persistence, fauna mortality, and damages to the local population (Kandus et al., 2009; Szpakowski and Jensen, 2019). In 2008, the main environmental impacts of the fires in the Lower Paraná River floodplain were related to the loss of soil organic carbon and nitrogen (Kandus et al., 2009; Salvia et al., 2012), which were emitted into the atmosphere and contributed to greenhouse gases: the cited authors reported that recovering soil carbon would demand 11 years. Biomass burning also affects fauna habitat, biodiversity patterns and economic activities (Kandus et al., 2020; Verzeñassi et al., 2020). Although herbaceous vegetation is recovered quicker than soils (Salvia et al., 2012), atmospheric emissions due to biomass burning can be important (Balladares et al., 1997; Sione et al., 2009).

5. CONCLUSION

Obtaining updated reports allowed us to quickly respond to peers, technicians, and journalists about the evolving fire situation. While the environmental conflict evolved and was being discussed in the media, dissemination articles and posts in social networks were shared. This work is an ecological application of spatial analyses conducted with open-source software (R, QGIS). By presenting this approach and results in FOSS4G 2021, I aim to highlight: the importance of using remote sensing data and ancillary geographic data to monitor large-scale disasters; how generating reproducible workflows can facilitate and improve geospatial analyses, and lastly, I want to spread the usage of open-source geospatial software to account all these tasks. The case study shows SIG, remote sensing and data visualization tools applied to a current environmental topic in South American wetland environments. The scripts can be adapted to other study areas to facilitate active fire monitoring.

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APPENDIX

A bilingual (English/Spanish) repository is available: https://github.com/nmorandeira/Fires_ParanaRiverDelta (doi: 10.5281/zenodo.4639806), with R scripts shared under a CC BY 4.0. license. Published dissemination articles, interviews and talks during 2020 (for which this work was useful) are also listed in the Readme.md file, as well as plots and an abstract in Spanish.