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EFFECTS OF MAN-MADE FIRES ON WETLANDS OF THE PARANÁ RIVER IN ARGENTINA: PERSPECTIVES OF ECOLOGICAL RESTORATION

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Abstract: Fire caused by man in South America is one of the most concerning environmental catastrophes, due to its potential impacts on global climate change. The aim of the present study was to determine the immediate effects of man-made fires on both the soil and the diversity of vascular plants and vertebrates present in the wetlands of the Paraná River (Argentina) during 2020, with emphasis on the perspectives of restoration in the short-term. In particular, we measured the depth of burning and listed the vascular plant and vertebrate species that were burned. We also collected field data of plant species by in situ observation (affected species, vegetal configuration, flam height on wood) and data on vertebrate species by visual encounter surveys. Species that could not be determined in situ were recorded by photographs for later identification in the laboratory. We also determined the difference normalized burn ratio (dNBR) and the normalized difference vegetation index (NDVI) before and after the fire event. The soil burned at a depth of 2-12 cm, whereas the flame heights ranged from 2.70 to 4.20 m due to the presence of woody species. At least, total of 46 plant and 39 vertebrate species were affected by fires. The dNBR index showed moderate (17.64%) to high (52.94%) burn severity. The NDVI values decreased by half compared to the values recorded in the control images immediately after the fire and showed low medium-term revegetation after three to four months. Since man-made fires in wetlands are likely to increase due to climate change in the coming years, there is an urgent need for legislation to regulate the conservation and restoration of these ecosystems.

Keywords: biodiversity; burned wetland; catastrophes; secondary succession.

INTRODUCTION

The biodiversity loss and climate emergency due to the pressure of human activities on natural habitats pose severe threats to humanity. Some of this loss and destruction are due to man-made fires, as those observed in the last years in woodlands, rainforests and wetlands of the

Amazon and Pantanal in Brazil, Australia and Argentina (*e.g.* Mega 2020). These disturbances have caused major social and ecological concerns and highlight the need to obtain information about the plant and vertebrate species affected by man-made fires, so as to be able to plan strategies to mitigate, conserve and restore them (Burton *et al.* 2021).

Wetlands include a wide variety of environments that are flooded or saturated by water, either permanently or seasonally, such as riparian forests, marshes, swamps and bogs, among others. Although there is no consensus on the wetland limits and nature, some authors have recently emphasized the need to consider the complex hydrogeomorphic characteristics into their analysis and inventories (Kandus *et al.* 2019). The largest surface covered by riparian wetlands is located in South America, associated with the Amazonas, the Orinoco, and the Paraguay-Paraná rivers. In Argentina, wetlands cover more than 21% of its territory (Morandeira *et al.* 2021). Degradation and loss of wetlands are global concerns because they harbor high biodiversity and ecosystem services, such as erosion control, hydrological regimen and water safety (Costanza *et al.* 2014).

Different authors have pointed out that the main drivers altering wetlands are climate and land use change (Burton *et al.* 2020). However, the reduction of the wetland carrying capacity by the expansion of livestock grazing has gained attention due to the indiscriminate use of man-made fires to remove non-palatable herbs, which ultimately affect wetland ecological integrity (Salvia *et al.* 2012, Kandus *et al.* 2019). In general, wetlands are not resilient to fires and plant species are not ecologically adapted to recurrent fires (Miller *et al.* 2019). The impacts of fires on the biodiversity and functioning of riparian wetlands are understudied, compared to boreal, temperate and tropical terrestrial ecosystems (Pivello *et al.* 2021). On a wider scale, fires affect global warming through larger emissions of greenhouse gases, such as carbon dioxide (Burton *et al.* 2021), while, at the regional and local scales, they alter the hydrological cycle, the soil, and the functioning and population structure of plant and animal species (Pausas 2017). In addition, fires produce greenhouse gas emissions and smoke pollution (ash, micro-particles), which affect the cardiovascular and respiratory systems of humans (Manisalidis *et al.* 2020).

In Argentina, riparian wetlands have experienced catastrophic man-made fires during the last years like never before, destroying more than 800,000 ha during 2020-2021 (SNMF 2021). It is believed that they are generated not only for cattle ranching practices (Baigún & Minotti 2021), but also for agribusiness purposes (*e.g.* crops, cattle and swine feedlots) and expansion of urbanization (Kandus *et al.* 2019). In this context, the aim of the present study was to determine the immediate post-effects of man-made-fires on the soil and the diversity of vascular plants and vertebrates of riparian wetlands of the Paraná River in Argentina, during 2020. We collected plant and vertebrate data based on field surveys and performed remote sensing analyses to obtain spectral indexes that indicated burn severity and vegetation health status. The data collected in field surveys are the first to describe the effects of man-made fires on wetlands of the Paraná River and could potentially contribute to increasing the awareness in the society and to promoting policies for their effective biodiversity conservation.

METHODS

Study area

The study was carried out in 17 burned wetlands of the middle section of the Paraná River, which extends along the Provinces of Santa Fe and Entre Ríos between 31° 26’ 27’’ S - 31° 54’ 05’’ S and 60° 20’ 40’’ W and 60° 46’ 17’’ W, in the east-central Argentina, from August and September 2020 (Table 1, Fig. 1). The wetlands were randomly selected, according to data on the occurrence of fire events obtained in near real time by the Fire Information for Resource Management System (FIRMS), a NASA application. It is important to note that the Paraná River is the second largest river in South America after the Amazon, being extremely important from the point of view of biodiversity and hydrology (Iriondo *et al.* 2007).

Table 1. Geographical location of the 17 wetlands of the Paraná River studied, with a brief description of the date on which the fire started, the date of field sampling and the characterization of their environmental units. Each wetland had a sampling effort of two people for three hours. Number, N.

	Wetlands Coordinates South-West		Locality	Province	Fire Start	Field Sampling	Environmental Units
1	31° 30' 24''	60° 23' 32''	Los Zapallos	Santa Fe	Aug 22 2020	Aug 24 2020	mid-slope and river bank
2	31° 33' 17''	60° 46' 17''	Near Los Molinos Country	Santa Fe	Aug 06 2020	Aug 08 2020	mid-slope
3	31° 34' 7''	60° 34' 47''	Laguna Setubal	Santa Fe	Aug 22 2020	Aug 23 2020	river bank
4	31° 35' 20''	60° 30' 14'''	Ubajay	Santa Fe	Aug 28 2020	Aug 31 2020	mid-slope, river bank and inner marshland
5	31° 35' 31''	60° 32' 11''	Ubajay	Santa Fe	Aug 28 2020	Aug 31 2020	mid-slope, river bank and inner marshland
6	31° 38' 30''	60° 39' 39''	Near El Pozo Suburb	Santa Fe	Aug 21 2020	Aug 22 2020	mid-slope
7	31° 41' 07''	60° 30' 32''	Near national road n° 168	Santa Fe	Aug 22 2020	Aug 23 2020	mid-slope and river bank
8	31° 50' 29''	60° 37' 02''	South area of Paraná city	Entre Ríos	Aug 17 2020	Aug 19 2020	mid-slope and inner marshland
9	31° 54' 05''	60° 39' 39''	Alvear	Entre Ríos	Aug 18 2020	Aug 21 2020	mid-slope and river bank
10	31° 37' 17''	60° 22' 44''	Villa Urquiza	Entre Ríos	Aug 17 2020	Aug 19 2020	river bank
11	31° 47' 43''	60° 43' 33''	Bajada Grande	Entre Ríos	Aug 17 2020	Aug 20 2020	mid-slope
12	31° 41' 22''	60° 30' 47''	Near national road N°168	Santa Fe	Aug 21 2020	Aug 22 2020	mid-slope
13	31° 26' 27''	60° 20' 40''	Santa Rosa de Calchines	Santa Fe	Aug 17 2020	Aug 19 2020	mid-slope and river bank
14	31° 42' 50''	60° 32' 48''	Parque Varisco	Entre Ríos	Set 16 2020	Set 19 2020	river bank and inner marshland
15	31° 38' 00''	60° 38' 33''	Near El Pozo Suburb	Santa Fe	Set 19 2020	Set 21 2020	mid-slope
16	31° 33' 13''	60° 29' 9"	Ubajay	Santa Fe	Set 19 2020	Set 19 2020	mid-slope and river bank
17	31° 33' 57''	60° 30' 32"	Ubajay	Santa Fe	Set 13 2020	Set 14 2020	mid-slope, river bank and inner marshland

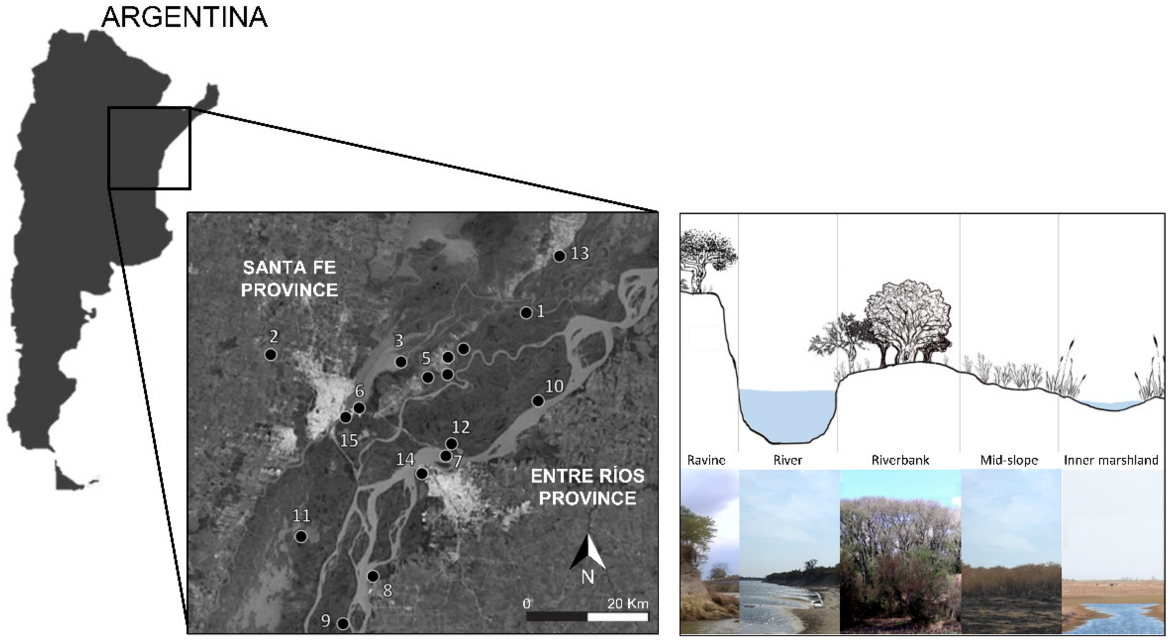

Figure 1. (a). Wetlands (black dots) distribution in the middle section of the Paraná River (South America) and (b) graphical representation of environmental units.

In situ evaluation of the soil, flora and fauna immediately after the fire event

Field samplings were carried out immediately post-occurrence of the fire event (IPF), between August and September 2020 (Table 1). To avoid removal of carcasses by scavengers or deterioration, samplings were carried out within 72 h of burning, but mostly within 24–48 h. A semi-quantitative sampling design, with a sampling unit defined by person-hours of effective fieldwork, where two people performed surveys for 3 hours in each burned wetland. Field sampling consisted of random walks and was carried out by two observers specialized in wetland ecology in each burned wetland, always avoiding potentially unburned areas. To track time spent sampling, observers used a stopwatch, which was stopped when they were busy with other activities (*e.g.* photography, measurements). The environment unit (s) (mid-slopes, riverbanks, inner marshlands, ravines) described by Kandus *et al.* (2019) was recorded in each burned wetland (Fig. 1; Table 1).

Vascular plants. Plant species directly affected by fires that had burned bark or burned fruits/seeds in the canopy or on the ground or which were found fallen on the ground were recorded. Burned plant species that could not be identified in the field were photographed using a professional digital camera (Nikon D 7000), and then identified in the laboratory by using standard field guides (Zuloaga *et al.* 2019) or by consultation with experts. Plant species were classified by their physiognomic strata (herbaceous, shrub, or tree, following Kuechler and Zonneveld 1988), and the vegetation configuration (open, semi-open, semi-closed or closed plant community) was recorded following Capelino & Bender (2020). In woody species, flame height (m) relative to canopy fuel was also measured as an indicator of fire intensity (Pausas 2017).

Animals. The animals present in each burned wetland were surveyed by a visual encounter survey carried out during the random walking. This survey included both direct (dead individuals) and indirect (feathers, feces, footprints, canopy nesting, holes on the ground) evidence (Key & Benson 2006). Vertebrate evidence that could not be identified in the field were photographed using a professional digital camera (Nikon D 7000) and later identified in the laboratory by using standard field guides and studies (Parera 2002, Giraudo & Arzamendia 2007, Peltzer & Lajmanovich, 2007, Pearman & Areta 2020) or by consultation with experts. Identified fishes and invertebrates were also listed (Supplementary files, Appendix S2,

Table 2 and Appendix S3 Fig. 1) but were excluded from the field analysis.

In situ severity characterization: The fire field severity in each burned wetland was characterized as recommended by Key & Benson (2006) and Pausas (2017). The fire severity characterization included the recording of 1) the soil depth affected by the fire, 2) the mean height of flame in woody species, and 3) the most affected woody plant or vertebrate species in the total wetland samples. Soil depth was measured with a meter rule (0.01 mm precision) in each burned wetland considering its environmental units. Three measurement replicates were recorded within the burned area of each wetland, always avoiding areas that were eventually not burned. Mean height of flame was measured with a measuring tape (0.5 mm precision).

The occurrence percentage was quantified to determine the most affected species was determined as the number of wetlands with each woody plant or vertebrate species directly affected by fires divided by the total number of wetlands studied.

Means of burned soil depth and height of flame in woody vegetation were correlated with the type of environmental unit and vegetation configuration by using the Spearman's correlation coefficient when normality assumption was violated, with the IBM version 18 software.

Remote sensing measurement of fire severity

Analyses of fire severity comprised spectral data given from one pixel georeferenced with Garmin 10 Geocaching Glonassat in the center of each wetland burned area and three adjacent pixels fixed around this waypoint on Sentinel-2 satellite images. Sentinel-2 MSI Level-2A satellite images (Google Earth Engine) were used for image selection and pre-processing of each pixel. The Sentinel-2-time series red (band 4), near infrared (NIR) (bands 8 and 8A), and short wavelength infra-red (SWIR) (band 12) regions were selected. The difference normalized burn ratio (dNBR) and the normalized difference vegetation (NDVI) indexes were used to analyze the impact of fire on the vegetation in each wetland. For each wetland, the dNBR and NDVI values were averaged by the data of the four pixels.

The dNBR was obtained and classified from the difference between the NBR pre- and post-fire (± seven days before and after fires, depending on satellite data availability), as recommended by Sobrino *et al.* (2019) and Downing *et al.* (2017). The dNBR was computed using Sentinel-2 20 m spatial resolution bands using the NIR (band 8A) and SWIR (band 12) regions.

Satellite images and spatial data were obtained to quantify the NDVI immediately post-fire (IPF) and three-four months post-fire (short post-fire period, MPF) in the total area. The NDVI was also determined one year before the fire (BF) to estimate the greenness condition before fire events (year 2019), and these values were used as controls (Yengoh *et al.* 2015). The NDVI was computed using Sentinel-2 10 m spatial resolution band at the NIR (band 8) and red (band 4) regions. The NDVI was used to monitor post-fire recovery of vegetation and values were classified according to Yengoh *et al.* (2015).

Relation of in situ and remote data

Different correlations of *in situ* field and remote data were performed. Field burn severity based on the dNBR index was correlated with the type of environmental unit burned and the vegetation configuration, using the Spearman's correlation coefficient when normality assumption was violated, with the IBM version 18 software. Also, the dNBR and NDVI IPF and MPF were correlated. In addition, NDVI values across the time series (BF, IPF and MPF) were analyzed with ANOVA and Tukey post-hoc test. In addition, a Wilcoxon pair test was performed to test whether vegetation recovered, based on MPF values of its previous reflectance or greenness values (BF). Regression between NDVI values IPF and MPF was performed to interpret variation between spectral values of the vegetation status after the fire event (Lacouture *et al.* 2020).

RESULTS

In situ evaluation of the soil, flora and fauna immediately after the fire event

The most affected environmental units were riverbanks (83%), followed by mid-slopes (47%), inner marshlands (17%) and ravines (5%). In burned wetlands, the soil was burned up to the first -12 cm, being the most affected environmental unit riverbanks (between -7 and -12 cm) and mid-slopes (-4 and -8). The depth of soil burning was correlated with the type of environmental unit (Spearman $r_{riverbank} = 0.95$; Spearman $r_{mid\text{-}slope} = 0.80$) and the configuration of the plant community (Spearman $r_{semi\text{-}closed}$ vegetation= 0.85). A greater depth of burning has been recorded in the soils of riverbanks and mid-slopes with semi-closed plant configuration ($p < 0.05$, respectively).

A total of 46 species of plants were listed in the burned wetlands and classified into three strata (Nherbaceous= 26; Nshrubs = 9; Ntrees = 11, Supplementary files, Appendix S1, Table 1). The occurrence percentage (%) showed six woody species that were most affected by fires: *Vachellia caven* (76%), *Tessaria integrifolia* (59%), *Albizia inundata* (52%), *Erythrina crista-galli* (52%), *Salix humboldtiana* (52%) and *Sapium haematospermum* (47%) (Fig. 2). The bark of trees was burned at first 5-15 mm (Fig. 3 a). The height of flame on woody species varied between 1.85 and 3.20 m. Dispersed seeds and fruits of *Sesbania virgata*, *V. caven* (Fig. 3 c), *A. inundata*, *E. crista-galli* and *S. haematospermum* were observed in burned soil.

A total of 39 species of vertebrates (Namphibians = 2; Nreptiles = 4; Nbirds = 24; Nmammals = 9) were listed in the burned wetlands (Supplementary files, Appendix S1, Table 2). The occurrence percentage (%), which was based on dead animals (for example Fig. 3f-l) or indirect

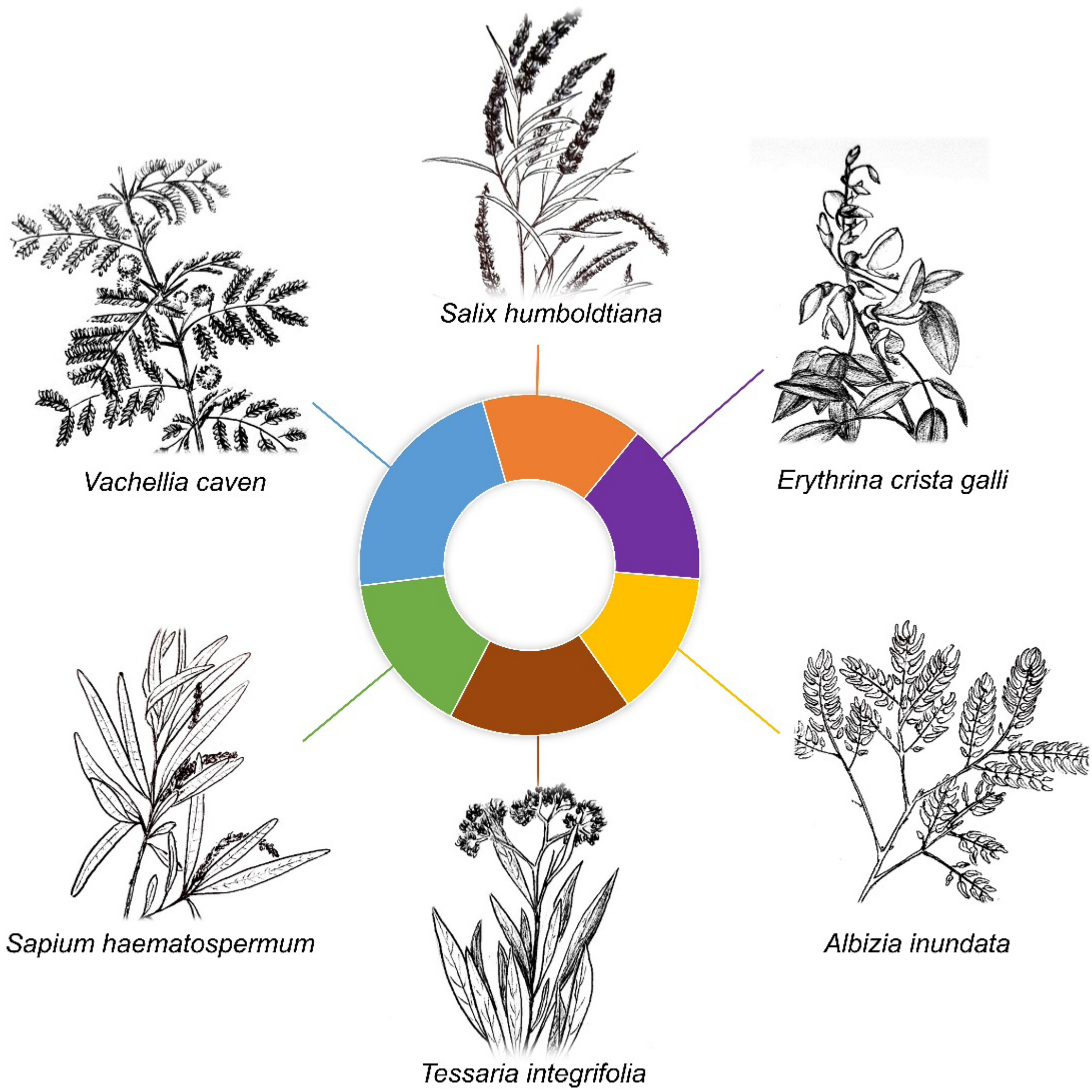

Figure 2. Percentages of the most fire-affected woody species in different wetlands of the Paraná River.

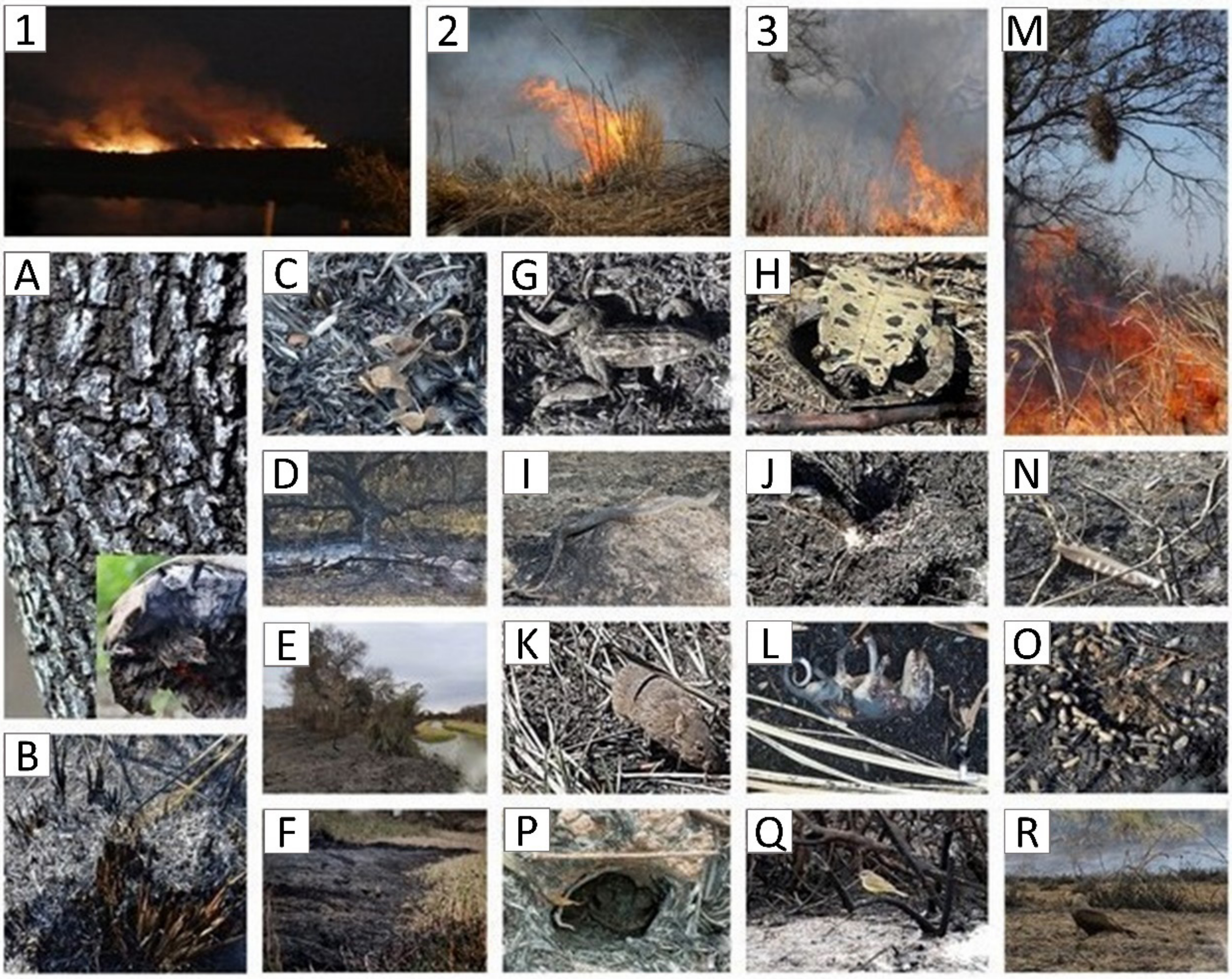

Figure 3. Fire on wetlands in the middle section of the Paraná River (1-3. different views during the night and during the day). Woody and herbaceous vegetation in environmental units (d. river bank, e-f. median-slope and inner marshland). a. burned bark showing a trunk of *Erythrina crista-galli* in detail; b. burned leaves of *Cortaderia selloana*; c. burned rests of seeds and fruits of *Albizia inundata*; d. *Vachellia caven* dying standing. Direct (f-l) and indirect (m-r) findings of burned vertebrates. f. *Leptodactylus luctator*; h. *Phrynops hilarii*; i. *Helicops leopardinus*; j. *Podiceps major* juvenile; k. *Holochilus brasiliensis*; l. *Didelphis albiventris* young weasel hatchling; m. flame near a nest of *Phacellodomus ruber*; n. feather of *Caracara plancus*; o. feces of *Hydrochoerus hydrochaeris*; p. cave with *Rhinella dorbignyi*; q-r. *P. ruber* and *C. plancus* resting on burned branches and soil.

evidences (burned feces, nest and holes; Fig. 3 m-r), showed the highest values for the following 16 species: amphibians: *Rhinella dorbignyi* (23%) and *Leptodactylus luctator* (12%); reptiles: *Phrynops hilarii* (23%), *Caiman latirostris* and *Helicops leopardinus* (6%, respectively); birds: *Vanellus chilensis* and *Caracara plancus* (41%, respectively), *Phacellodomus ruber*, *Furnarius rufus* (23%), *Hymenops perspicillatus*, *Ardea alba* and *Jacana jacana* (18%, respectively); and mammals: *Hydrochoerus hydrochaeris* (41%), *Myocastor coipus* (35%), *Oligoryzomys longicaudatus* and *Holochilus vulpinus* (12%, respectively) (Fig. 4).

Analysis of remote data: burn severity and vegetation index

Sixteen of the studied wetlands differed in the burn severity index (dNBR), showing moderately high severity values (52.94% complete canopy scorch), high severity (17.64% total or partial canopy scorch), moderately low severity (17.64% partial canopy scorch), and low severity (5.88% unburned canopy). One wetland had enhanced low regrowth (5.88% unburned understory vegetation).

Results also showed a correlation between the mean height of burned vegetation, woody configuration, and dNBR (Spearman r = 0.95

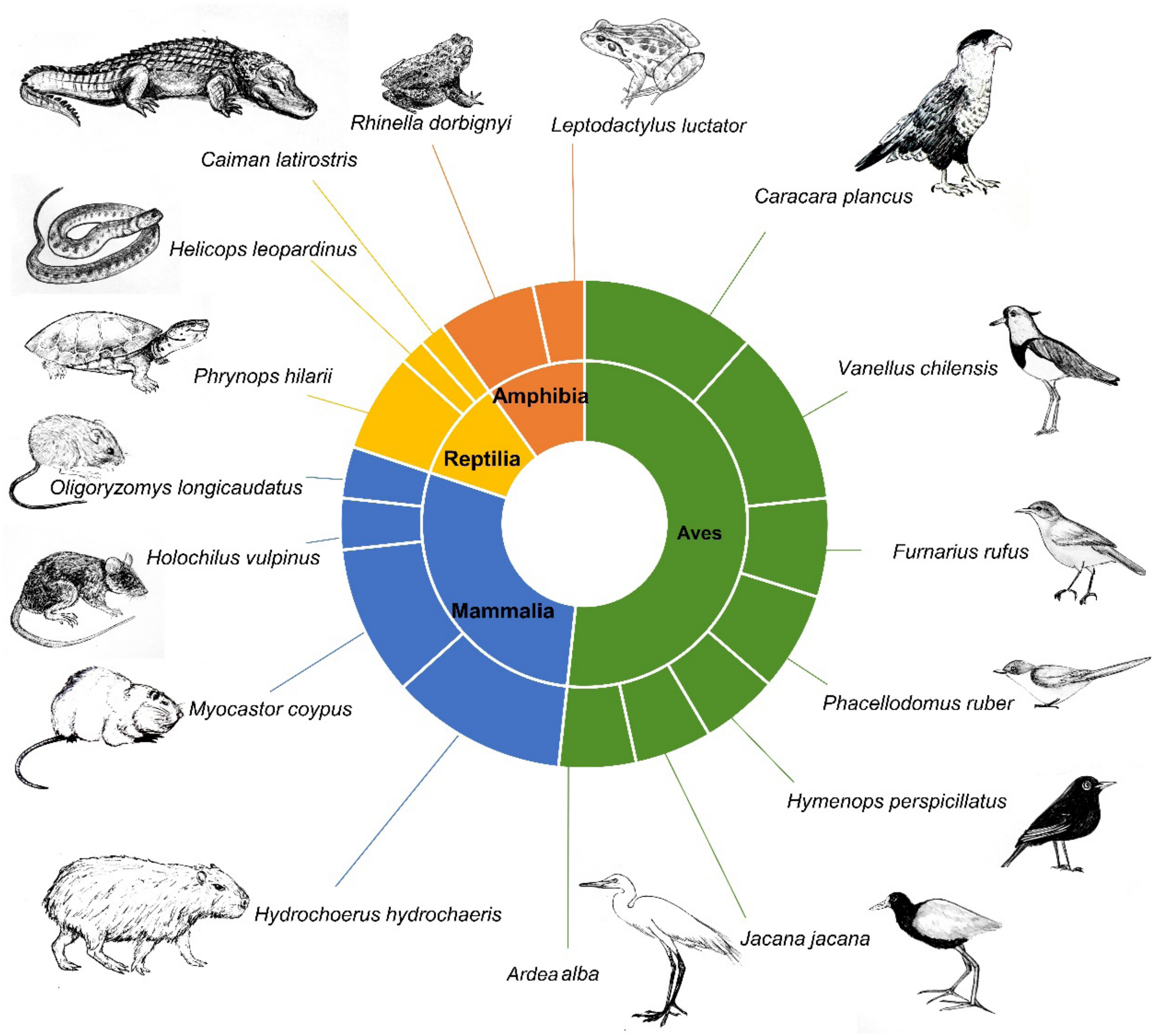

Figure 4. Percentages of the most fire-affected vertebrate species in different wetlands of the Paraná River.

and 0.98, respectively), being woody vegetation the most affected in wetlands with semi-closed vegetation and high severity dNBR values ($p < 0.05$).

The BF, IPF and MPF NDVI values varied significantly (ANOVA F = 31.36; $p < 0.00001$) in all the wetlands monitored (Tukey's post-hoc test < 0.001). The values were higher before the fire (NDVIBF = 0.73 ± 0.13), decreased by half immediately post-fire (NDVIIPF = 0.33 ± 0.14), and slightly increased after a short period post-fire (NDVIMPF = 0.49 ± 0.01). The BF and IPF NDVI values were statistically different (Wilcoxon test Z NDVI BF-MPF = 3.006; $p < 0.01$), and there was no linear relationship between the IPF and MPF NDVI values (linear regression r2 = 0.29, p = NS).

Values of dNBRIPF and NDVIIPF were significantly correlated (r Spearman = -0.45, $p < 0.05$), indicating that remote sensing values of burn severity were related with low reflectance (visible and near-infrared) of vegetation immediately after the fire event. Similarly, dNBRMPF and NDVIMPF were negatively correlated (r Spearman = -0.60, $p < 0.05$) after three-four-months post fire.

DISCUSSION

Riverine wetlands are highly vulnerable and may be irreversibly altered by fire (Stevens-Rumann *et al.* 2018). Our study provides the first detailed data of the immediately effects of man-made fires on the soil and the vascular plant and vertebrate species of the wetlands of the middle Paraná River in Argentina. Our results showed that the fire affected the first -12 cm of the soil, and we have evidence of a direct impact on 46 species of plants and 39 of vertebrates, highlighting the negative ecological consequences of fires.

Most studies on the effects of fires in this region have focused on the use of remote sensing techniques (eg Sione *et al.* 2009; Salvia *et al.* 2012; Zamboni 2013, Valle *et al.* 2022) and there are few scientific studies that quantify the loss of biodiversity after fire in wetlands of the lower Paraná River. A recent review of the responses to fire of burned and unburned areas that indicated the recovery of invertebrates abundance, the reduction of vertebrates abundance, and the losses of nitrogen and organic matter coincide with the responses found in global reviews in short times after fire in South American ecosystems (Giorgis *et al.* 2021).

The plant and vertebrate species listed for the 17 burned wetlands of the middle Paraná River are frequently found in their wetlands (detailed in several chapters by Iriondo *et al.* 2007). It is important to note that the *in situ* field sampling here performed coincided with the end of the winter season, therefore annual climbing herbs or shrubs (*e.g. Melothria candolleana*), or spring-summer breeding or juvenile vertebrates (*e.g.* amphibian: *Boana raniceps*, reptile: *Hydrodynastes gigas*, bird: *Tyranus savanna*, heron: *Nycticorax nycticorax*; otter: *Lontra longicaudis*) were not recorded. Regarding to the great biodiversity of wetlands, it can be suggested that if the fires had occurred during the flowering, fruiting or reproductive (spring and summer months) seasons of most of Paraná River plants and vertebrates, fire effects would have been even greater. Although we found a greater percentage of herbaceous plants in burned wetlands, some other herbaceous species listed by many authors (*e.g.* Peltzer 1998, 2006, Salvia *et al.* 2012, Kandus *et al.* 2019) were not found in the wetlands studied, probably because some species completely consumed by fire before field sampling or their phenology. As it was previously reported by Zamboni *et al.* (2013), the fires at the Paraná River Delta affect mainly the herbaceous vegetation and the seasonal pattern of occurrence is usually in early spring to early summer. The limitation of this field study was the fraction of species that were directly affected by the fire and could not be found during sampling due to their phenology. Therefore, the observable effects of the fires in these wetlands could have been worse if the non-observable species consumed by the fire or those species that due to their seasonal phenology were not developed were considered, so future studies should be considered these data. In addition, further studies should evaluate the effects of microhabitat and trophic resource loss after fire as well as the viability of seed banks and plant bulbs and the success of vertebrate reproduction during long study periods.

Our results also showed that fires did not cause mortality of high trees (> 4 m) such as *A. inundata* or *S. haematospermum*. However, fires had their bark, foliage and secondary branches burned. Thin barks have generally been associated with woody species living in ecosystems with no regular fire regimes such as wetlands (Pausas & Keeley 2019). Similarly, wetland woody species have no key strategies to escape fire such as early height growth (the lanky strategy) or early bark growth (the corky strategy). Studies on the viability of wetland woody species after several fires of different intensity (flame height) and frequency should be performed to understand the pressure of fire on the inner and outer barks of wetland shrubs and trees (Pausas 2017). Moreover, leaves of some plant species such as *E. crista-galli* fall off in winter, a trait that could prevent the flame from reaching higher (Rodríguez-Arias *et al.* 2018).

The differenced Normalized Burn Ratio index (dNBR) revealed that the wetlands of the Paraná River studied presented moderate-high burn severity. The dNBR values were consistent with those of *in situ* severity data and are in accordance with those reported by Salvia *et al.* (2012) in Delta Paraná River for 2008-2009 period. The NDVI values obtained determined that revegetation in burned areas of the wetlands was still affected after three-four months post fire. This low level of revegetation may be explained by the fire severities and the extraordinary Paraná River drought, in agreement with that pointed out by Kirkman (1992) for Kwambonambi wetlands. In a recent study of the Paraná River Delta burned wetlands, del Valle *et al.* (2022) also highlighted the influence of drought in vegetation dynamics in fire assessment and monitoring by the use of radar and optical data. Moreover, these authors propose that relationship between the landforms, vegetation cover, and the spatial and temporal resolutions imposed by the flood pulse, play a vital role in the quality of remoting data analysis. In this sense, the complement of the remote analysis with the records *in situ* may help to expand the vision of integrative fire monitoring and assessment. The relation between fire severity (*e.g.* burn depth in soil) and the natural restoration of vegetation (at both field sampling and spectral analyses) should be considered in the management of burned wetlands, for example, when monitoring stocking effects on these areas. Moreover, this information of vegetation growth and restoration (*e.g.* type of resprouting) that often occur in spring and summer is needed before starting active restoration activities (Gann *et al.* 2019).

Thus, it is important to note that moderate to high intensity fires during the dry season may destroy roots and rhizomes of plants, as well as organic matter, and may volatilize nutrients, leading to the recolonization of opportunistic species, affecting secondary succession (Rodríguez-Arias *et al.* 2018). As different authors have already pointed out, after a fire event, exotic species proliferate quickly, and active restoration methodologies (e.g. cutting, seedling removal) should be performed, removing these species or renewals as soon as possible (Christensen *et al.* 2019). Several exotic plants such as *Gleditsia triacanthos*, *Ligustrum lucidum*, *Ricinus communis*, and *Maclura pomifera* are commonly found in wetlands (Kalesnik & Quintana, 2006), causing exclusive competition with native plant species such as *Inga affinis*. Thus, an adequate management of the potential invasion of exotic plants in burned wetlands should also be considered.

Since wetland plant and animal species perform key ecosystem functions, the loss of these species can cause important declines in wetland resistance and resilience after a disturbance (Chambers *et al.* 2019). Some bird species play important roles in wetland restoration due to their ability to disperse seeds (Beltzer 1990). An example of this is *Embernagra platensis*, which disperses seeds of *Urera aurantiaca* and *Muehlenbeckia sagittifolia* (see detailed information regarding the potential role of each bird species in ecological restoration in Supplementary files (Appendix S4, Table 3). In addition, several vertebrates persist in wetlands after disturbances, as observed in our study for *C. plancus*, a scavenger bird species (Supplementary files, Appendix S2, Table 2), which could facilitate wetland restoration.

During the period evaluated, the wetlands of the middle section of the Paraná River studied were severely damaged by man-made fires, a fact that affected natural restoration. A total of 83 species of plants and vertebrates were immediately affected by fires during the period studied. Results showed burned seeds and fruits on soil banks, partial or total damage of bark in woody species, loss of habitat (*e.g.* nests, refuges), and burned soil in the first 12-cm, mainly in riverbanks and mid-slope environmental units of burned wetlands. Besides, satellite-remote analysis demonstrated that wetlands had moderate-high severity burn and a decrease in vegetation reflectance after fires.

The likelihood of apocalyptic and catastrophic fires (Mega 2020) on wetlands tend to increase due to the climate change, the extraordinary drought of neotropical rivers, the absence of "*flying rivers*", urbanization, and the expansion of livestock and genetically modified crops (Marengo *et al.* 2018). These scenarios could also disrupt the ecological function of wetlands, such as the Pantanal and the Paraná River wetlands. The mitigation of these anthropic activities may be all that is required to conserve and restore many degraded wetlands (Batchelor *et al.* 2015, Rodríguez-Arias *et al.* 2018). It is also necessary to deep on the study of other indicators of the consequences of fires in wetlands, such as the high CO2 emissions that these events produce. A study of the Delta Paraná region in 2007 estimated an emission between 18 and 34 Mg of C per hectare, with a total of more than 7.7 Tg C-CO2 per year, which is comparable to the annually produced by an Argentine city with 2000000 inhabitants (Sione *et al.* 2009). In this sense, the estimation of carbon emissions must be studied at present, when fires are increasing both in frequency and extension. In addition, this issue is essential for new monitoring in the affected region.

The popular claim for wetland conservation and restoration activities through South America highlights that policy-driven approaches (top-down), should be linked to the complex eco-hydro-morphological wetland view, scientific evidence and the cultural and local needs (bottom-up), as has been noted for riparian forests (Meli *et al.* 2019). The effects on flora and fauna of man-caused fires related to livestock, agricultural activities and the expansion of urbanization have been highlighted in this manuscript, and should be considered in public policies and new legislation, such as the postponed "Argentina Wetlands Law", which promotes sustainable use, management and protection of these ecosystems. Appropriate public policies and implementation of effective law enforcement are essential to curb deforestation and fire (Cardil *et al.* 2020), and therefore, the wetlands ecocide.

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SUPPLEMENTARY MATERIAL

Appendix S1. Table 1. List of vascular plants (N, number of species) recorded in burnt wetlands of the Middle Paraná River (Argentina). The list of species was classified by strata (herbaceous, shrub and tree).

Appendix S2. Table 2. List of animal species recorded in burnt wetlands of the Middle Parana River (Argentina) based on visual encounter surveys of dead individuals (M), indirect evidences (IE: feather, nest, feces, holes), or direct observation of resistant (R) individuals flying or feeding in burnt areas.

Appendix S3. Figure 1. Invertebrates and fishes affected by fires in Middle Paraná River wetlands. Different views of environmental units burning (1. River bank, 2. Mid-slope) and burned (3. Mid-slope; 4. Inner marshland; 5 inner marshlands with *Caracara plancus* waiting for sublethal preys). A-B. *Polybia occidentalis*. C. Ants corridors. D. *Pomacea canaliculata*. E. *Zilchiopsis collastinensis*. F. Serrasalminae. G. Fishes mass mortality (Loricariidae, Characidae, Callichthyidae and Prochilodontidae). H. *Prochilodus lineatus*. I. *Hoplosternum littorale*. J. Loricariidae.

Appendix S4. Table 3. List of Bird species that potential contribute to wetlands restoration due to its biological function (habitat use and trophic guilds) and briefly notes of their presence on wetlands and riparian forests.

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