Critical jaguar habitat destroyed by fire in Pantanal

Authors & affiliations:

Alan Eduardo de Barros (PhD student)[1]

Paulo Inácio de Knegt de López de Prado (Supervisor)[1]

Ronaldo Gonçalves Morato (Co-Supervisor)[2].

This manuscript is still under development and may include other collaborators who provided data (Morato et al 2018a) or helped in the analysis prior to submission. *Correspondence: alanbiology@gmail.com

[1]Instituto de Biociências, Departamento de Ecologia, Universidade de Sao Paulo, Rua do Matão, Trav. 14, no. 321, Cidade Universitária, São Paulo, SP, 05508-090, Brazil.

[2]Centro Nacional de Pesquisa e Conservação de Mamíferos Carnívoros, Instituto Chico Mendes de Conservação da Biodiversidade, Atibaia, SP 12952011, Brazil. 12945010, Brazil.

Abstract

Brazilian Pantanal's 2020 fires erupted from a combination of intense drought, climate change, underestimation of land and water use impacts, as well as deactivation of personal, infrastructure and preventive plans, what resulted in a tardy combat response. In order to understand the reach and intensity of fire affecting priority areas for conservation in Pantanal, and how exceptional impacts in 2020 were, we investigated Pantanal's fire occurrences within home ranges (HRs) of resident jaguars and Protected Areas (PAs) over the last 16 years. The 2020's fires were the severest documented and affected about 33% of Brazilian Pantanal and 62% of Pantanal PAs. Fire occurred in HRs of 78% (35 out of 45) of the resident jaguars, with a median of 77% of HRarea burned (97% in Pantanal North). Furthermore, an average of 61% of PAs within HRs (median of 97%) were burned. Considering that fires hit the HRs of a top predator and an umbrella species with such brutality, and that even have hurt directly several individuals, it is certain that fires had struck also species with less mobility. Displacement, hunger, dehydration, fight for territories, lower reproducibility are derived consequences which may impact population sizes and ecological balance. A solution to prevent recurrence of such mega-fires lies in combat the anthropic causes which may intensify drought conditions, implementing actions such as the protection of springs, increasing number and area of PA, restricting use of fire and allocating fire brigades ahead the dry seasons.

Introduction

Jaguar (*Panthera onca*) conservation status has been assumed as Near Threatened from a quarter of a century[1]. While several subpopulations have already been recognized as endangered or critically endangered[1–4] the assumed stability of subpopulations in Amazon and Pantanal are under crescent stake because accelerated intensification of land use in these areas. Habitat loss, poaching of prey or as retaliation due to livestock depredation, pollution by mining and pesticides, increase in agricultural activities and human infrastructures (escalating roadkills for instance) are among the major recognized threats to jaguar conservation in Pantanal[3,5–11]. Whereas fire is usually considered as likely to cause fluctuations in small portions of jaguar population[1,3], the unprecedent gravity of fires in Pantanal[12] in the past year suggests an example of miscalculated risk.

Abnormal fires in Brazilian Pantanal started already in 2019 wet season and intensified along with the dry season[12–14]. Fires encompassed 30-33% of Brazilian Pantanal, corresponding to 45-50 thousand Km^2 (estimates derived respectively from LASA[12,15] (using a reference period from Jan - Nov 22, 2020 and 500 m resolution) and this study (reference period from Jan - Dec 31st, 2020 and 1 Km resolution). This is an unprecedent record considering that the estimated average for the previous 15 years corresponded to 10% of the Pantanal area. And the number of fire foci registered in 2020 by the National Institute for Space Research (INPE) were 400% greater than the estimated historical median (1998 to 2019 interval)[14,16]. Ignition initially caused by human land use [12,13,16–23], low precipitation rate[24,25] and a pronounced drought[21,26–29] (SI_Fig.S1-S2) configurate the drastic scenario which fueled those extensive fires. Likewise it happened in Australia[30], the fire extended over ecosystems that typically do not burn, spreading underneath the soil and crossing through areas which would normally be flooded or close to water bodies [12,13,16,21,26].

As a result, the damage caused by fires can be in fact severer than the above announced burned area because fires consumed considerable portions of forest cover and areas of high ecological importance, which would otherwise provide shelter, food and landscape connectivity to several species[22]. The destruction of extensive areas of Protected Areas (PAs) (such as PARNA do Pantanal Matogrossense, Sesc Pantanal, PE Encontro das Águas)[12,15,21,22], forest patches at higher elevation areas (cordilheiras) and low-land riparian vegetation, or of keystone species of trees which provide fruits or contain hollows required for birds nesting (e.g. for Hyacinth macaw - *Anodorhynchus hyacinthinus)* are examples of how impact of fire may have disproportionally affected regions, species and individuals in Pantanal[12,21,22]. Besides, resistance and resilience abilities vary in plants[31,32], as well as the motion capacity in animal species[33], and this affect the responses of different species to escape, survive and persist in burned landscapes[30–33].

Although water pulses and fire regimens in Pantanal have a historical role to promote richness and shape riparian forests in wetlands[31,32], if the absence of flood and the excess of fire become a new tendence it may diminish overall resilience, in particular of the more vulnerable species[31,32]. Considering recent and predict increase in Global and regional temperatures[34–36], the repetition of scenarios of extreme drought and uncontrollable fires are a risk. On top of that, the negative effect of fire on gross primary productivity (GPP) has been found to be higher in Pantanal (with reported decrease in GPP of 55.78%) than in Amazon and Cerrado (which decreased by 44.20% and 30.04% respectively)[37]. In practice, reduction in GPP may reflect low productivity, which can result in a trophic cascade affecting several species.

While numerous researches on causes and consequences of 2020's extreme fires in Pantanal, and how it disproportionately impacted different species are needed, a fundamental first step is to understand the dimension and severity of these impacts. A key point is to evaluate fire impacts in Protected Areas (PAs), which are vital zones to the conservation of several species. On the other hand, PAs currently occupies only 4%[38] to 5.5%[39,40] of Brazilian Pantanal, with no more than 3% addressing integral protection[38]. Besides, representativity of PAs of integral protection in the entire Upper Paraguay River Basin (UPRB) are still low (5%), as well as in the adjacent biomes[41]. Given the low extension of Pantanal PAs, it is important to consider an alternative approach, which could also account for fire impact on zones of importance to the conservation of several species within the biome. We tackled this necessity by addressing how fire impacted home ranges (HRs) of an umbrella species, the local top predator, the jaguar (*Panthera onca*).

Jaguar presence and the establishment of a HR may be indicative of habitat quality, i.e., with presence of an adequate number of prey species, partners, shelter and ambush sites as well as other resources[42–45]. Jaguar HRs in Pantanal are among the smallest across the species geographical distribution[44,45], which is deeply connected with the high productivity (and the consequent density of prey) and vegetation cover[42,44,46,47]. Besides, the jaguars from Pantanal are larger in comparison to other study sites[42,47,48], a fact which also couple with the high density of prey.

We used available Geographic Information Systems (GIS) layers of PAs[38] and HRs of 45 resident jaguars from Brazilian Pantanal[48] to assess yearly impact of fires from January 1st 2005 to December 31st 2020[49–51]. Available jaguar GPS tracking data[48] for Pantanal (n = 55) ranged from 2005 to 2016, and originated from seven distinct study sites, three from the North and three from the South part of Brazilian Pantanal, and one from Paraguayan Pantanal. More specifically, the monitored individuals were spatially and temporally clustered[48] (SI_Fig.S3,S4,S5). For this reason, seeking for representativity, we assumed HRs as stable areas capable either to maintain a resident animal, or likely to be occupied and sustain a new individual if conditions were kept similar. An equivalent rationale is commonly adopted in approaches which estimate minimum population sizes from HRs estimates derived from tracking or camera trapping data[52–55], often with posterior use in conservation planning (e.g. to attribute IUCN categories classification[1–4]). We also excluded individuals with insufficient data (n=3), not residents (n=4) or from Paraguayan Pantanal (n=3) from the main analysis(SI_Fig.S3,S4,S5).

Comparing the last 16 years, we estimated: I) The percentual area of Pantanal impacted by fires each year. II) The extent of PAs in Brazilian Pantanal impacted by fire. III) The number of resident jaguars impacted by fire and the extent of their HRs burned each year. IV) Finally, we assessed the quantity of PAs, as well as their yearly burned extents, within individual jaguar HRs. We focused mostly on the assessment of the consequences of fires, rather than investigating the causes, but we included extensive data (see SI) and citations to support a related discussion. Nonetheless, we encourage further investigation, as well as the advance and the implementation of public policies[17,56] based on insights from scientific knowledge[19,21,22,39,41,57–60], capable to secure biodiversity conservation in the Pantanal biome.

Results

Our results show that: I) the 2020's fires were the gravest documented in extension and intensity (brightness temperature) (Figs. 1, 2 and 3) and consumed about a third (33%) of Brazilian Pantanal, a value three times higher than the calculated historical average based on the 15 precedent years. Besides, the average of 2020's documented fire intensity (352.3 K) was the highest among the years evaluated and overcome by 17 Kelvin the historical average (335.3 K). The severity of damage; however, reached higher proportions within PAs and jaguar HRs (Fig.1). II) About 62% of the PAs in the biome were burned. That is terrifying considering that these areas were designate as priority areas for conservation of jaguars and overall biodiversity. III) Overall, 78% (n = 35 out of 45) resident jaguars had their individual HR affected by fire in 2020 (Fig.2). With burned HR area corresponding to an average of 61%, and a median of 97% (Fig.3). This is 5.5 times higher than the historical mean (10%, considering the 15 precedent years). Major impacts happened in the Pantanal North, with an average of 87% of HRs burned (and a median of 97%) (Fig.3). IV) Percentage of PAs within jaguar HRs corresponded in average to 27.5%. About 53% of the jaguars had PAs burned within their HRs, with an average burn of 60% (median of 96%) in relation to the total available for jaguars (Fig.3). This value were about five times greater than the average of mean values of precedent years (12%). Fire impacts in PAs were higher in the North, where the average area burned within HRs reached 91% (and median of 100%) (Fig.3).

The historical comparison showed clear tendency of increase in fire extension and intensity over the last six years (Figs.1, 2 and 3). Besides 2020's, years of 2019, 2005, 2007, 2010, 2011 and 2013 also deserved some note (Figs.1, 2 and 3, see SI_notes for details). Among these years, except for 2020, 2005 was the most impacted. And differently than in 2020, during 2019 the fires affected mostly the South part of Pantanal. Fire occurrence and intensity in those years, however; did not rival with the aggressive destruction caused in 2020 (Figs.1, 2 and 3).

In parallel to the main analyses described above, in which the design was thought to include 2020's fire impacts and to extrapolate the assessment through a broader area over time, we also conducted a reference analyses considering fires that occurred within jaguar HRs only during each individual monitoring period (years 2008 to 2016 in Brazil and 2005, 2006, 2010 in Paraguay SI_Fig.S3,S4). Results from reference analyses were congruent with the main analyses and revealed that 2011 and 2013 fires had the highest impacts on jaguar HRs in Brazil (average of 20% and 31% respectively) (SI_Fig.S3a). Some data not used in the main analyses, belonging to jaguar from Paraguayan Pantanal or not resident (SI_Fig.S3b) also corroborated with our main findings (Figs.2,3). The HRs of three resident individuals from Paraguayan Pantanal suffered similar fire impacts as the reported to Brazil in the respective years, with highest impact occurring in 2005 (one individual with 92%) and 2010 (other individual with 34%) (SI_Fig.S3a). In addition, other four not residents' individuals from Brazil, which were monitored in years with low or mild impacts of fire, registered negligible effects (SI_Fig.S3b).

Along with the fires, the severity of 2020's drought has been documented by several episodes of animal famine, dehydration, burn and death[12,22]. A multitude of reasons may have contributed to the intensity of 2020's drought in Pantanal, from climate to human direct and indirect impacts in the Upper Paraguay River Basin (UPRB). Shortage of rain in the entire UPRB is certainly among the villains because UPRB water balance controls the hydroclimatological dynamics in the Pantanal (Fig2, SI_Fig.S1,S2, see methods for details)[61]. Such shortage could also be consequence of the crescent deforestation in Amazon rainforest[62,63], as the rate of summer rainy days in Pantanal is greatly associated to the Amazon climate variables[64].

In several gauge stations of the Paraguay river the water levels went below historical medians, or even below the historical minimums (Fig2, SI_Fig.S1)[26–28]. This leaded to the absence of floods and resultant retraction of wetlands area which provided inflammable material and opened the way for fires[21,22], which in most of cases were originated by humans[12,13,17–19]. Reduction on wetland flooded area seems to be historically correlated with spread of fires (Fig2, SI_Fig.S1)[21,31,32]. In this context, scientists have advertised that the dynamics of the burns do not keep up with the intensity of extreme drought years[37].

Using data from four stations of the UPRB (Corumba, Caceres, Cuiaba and Campo Grande) we estimated October–March 2019 -2020 rainfall to be about 25% below a historical average of monthly medians (reference years 1967-2019, SI_Fig.S1,S2, Fig2)[25]. Other work compiling several automatic stations, and using 1981-2010 interval as reference, estimated wet season to be about 57% below the normal expected (SI_Fig.S1b,c)[12,24]. While this shortage of rain could already be an effect of climate change, as a combined effect of carbon pollution from Global emissions and national deforestation[35,36,64], hydrological historical series show that extreme drought had happened in the past[35,65–68] (e.g. in late 1960's[35,66,68], SI_Fig.S1)[25–28]. A critical point; however, is how human actions can exacerbate such extreme events[41] as well as increase the difficulty to control fires (Fig.4). The fact is that last year abundant sources of human induced fires combined with the hottest and driest conditions documented since 1980 resulted in the year of 2020 receiving the highest daily severity rating index (DSR) for the period (1980 to 2020)[12].

Until 2019, native areas in Brazilian Pantanal were estimated around 84%, with most of anthropic areas covered primarily by pastures (15.5%) and secondarily by agriculture (0.14%) [29]. Pasture areas within Pantanal increased by 9 times in Mato Grosso do Sul (MS) and by 5 in Mato Grosso (MT) since 1985[29]. Even though occupying a smaller area, agriculture increased by nearly 50 times in this period within Pantanal[29]. In the Cerrado biome of MT and MS states, pasture and agriculture totalized 53% in 2019 (and increased about 2.08 times in MT and of 21% in MS between 1985-2019, SI_Fig.S5b) [29]. More importantly, is that agriculture and pastures have occupied from 60% to 65% of the surrounding Cerrado uplands within the UPRB[19,39,57], with a similar trend in the adjacent Paraguayan Chaco and Bolivian Chiquitano Forest[39,69,70], consequently impacting the main headwaters of Pantanal rivers and ultimately the Pantanal[19,41,57,58]. On top of that, these estimates[29], which are based on Landsat satellites with 30m resolution, may be underestimating understory degradation[19]. Alho et al. described in their work areas of cordilheira forest patches, or cerrado and cerradão, denoting anthropic occupation at different regions of Pantanal (e.g. understory trampled by cattle, burned and with fallen trees, clearings, excess of pioneer species, exotic species, fences, rubbish and cemeteries among other signals of use). And the history of fires itself (Fig.1) also suggests the possibility of disturbances in areas assumed as natural based on the Landsat resolution.

Considering only the last 15 years (2005 to 2019), a coincident period with our estimated impacts of fire on jaguar HRs, the implementation of pastureland in Pantanal deaccelerates, but still increase by 23%, while agriculture increased by 6.8 times (SI_Fig.S5a)[29]. Total area for pasture and crops tended to stabilize, increasing only about 3.5% in the adjacent upland areas of Cerrado (MT, MS) (SI_Fig.S5b)[29]. Worth mention an apparent shift of a parcel of pastures to soy crops since year 2000 in these Cerrado areas of these states[29], which couple with the slight reduction of total number of livestock in MS until 2018 (SI_Fig.S5a,b)[71]. Human population (MT, MS) increased by 25% in this period[72]. Furthermore, the tiny area occupied by urban infrastructures (0.04%) and mining (0.005%) by 2019 in Pantanal and adjacent Cerrado (0.2% and 0.006% respectively) [29] may not reflect the dimension of their impacts[41]. Transportation of mining products, for instance, are deeply connected to impacts of waterways in standard conditions[73], but under the 2020-2021 drought it have been related to roadkill increase in the main Pantanal highways due to the intensification in the transportation of mining products by trucks as a substitute[74]. Bearing in mind that Pantanal occupies only 38% of the UPRB[68], the cumulative impacts from economic activities and infrastructures in the surrounding plateaus affect the Pantanal in different ways (Fig.4, see SI_notes for details), including the drainage dynamics, flood pulses and drought extension which were intimately related with the spread of fires in 2020 [12,16,21,22](Fig.1 and 2, SI).

Meanwhile, the majority of the 30%[12,15] to 33% of Brazilian Pantanal burn probably happened within the 84% of natural cover remaining. Even though the exact amount of natural cover burned still need to be investigated in detail, it is certain that 2020's fires have destroyed in months more than the accumulated 16% of natural areas converted to anthropic areas over the last 35 years[29]. An impact of such magnitude cannot be ignored by decision makers. In addition, Global temperatures may increase up to 1.5° C through the next five years[34], on top of the 2° C already registered since 1980. With estimated increase of 5−7°C and 30% reduction in rainfall by the end of the 21st century[34–36]. This scenario is likely to keep or intensify drought conditions in Pantanal considering that the amount of rainfall was still below normal in the first three months (Oct-Dec) of current wet season (SI_Fig.S1b[24]). Therefore, existing risk that a tragedy, similar to the 2020's fires, can repeat (Fig.4). To make that worse, Governmental financial resources applied through the Ministry of Environment have been reduced to the lowest level in the last 20 years[75,76] (70% below the authorized level for year 2000), with serious complaints of misuse [77]and embezzlement[78] by the minister and the militaries in charged. Besides, against all the odds the planned amount to control and combat fires in 2021 have been reduced by 38% in relation to the amount designed to 2020 (and by 53% in relation to 2019) [75].

Discussion

Our intention here was to evince the catastrophic impact of 2020's fires and reveal that the percentual impact of fires on PA and on the HRs of an apex predator and umbrella species was about the double than the burnt estimated percentual for Pantanal. Continuity on decontrolled fires will diminish resilience and survival of jaguars and several other species. Besides the direct impact of fire causing deaths, charcoal and ash contaminate rivers poison waters and increase erosion[12]. And the impoverishment in resource availability impacted all the ecosystem, including jaguars and their preys. Even if fire negative effect on gross primary productivity (GPP) decreased only by previously estimates of 55.78%[37], it would already create significant impact disrupting ecosystems and food chains[12]. Worse than that, repetitive occurrences of exceptional burns can vanish the most sensitive species, replacing forest with open landscapes poorer in resources[12,31,32].

There is a relationship between small HR sizes and high density of jaguars in Pantanal[44,45]. Both can be attributed to a greater amount of preferred habitat and prey in a productive system which allows for smaller spatial needs[44]. Therefore, an immediate result of a sudden collapse of resources may be fights to establish new territories and movement adjustments to deal with lower prey densities in a less productive system, with potential extension of home ranges. Jaguar average weight may reduce, and reproduction may be affected. Death or displacement of jaguars because of fires has been estimated in more than 500 individuals for 2019's fires in Brazilian and Bolivian Amazon[79,80]. And an extend period of evaluation (2016 to 2019), for Brazilian Amazon, projected death or displacement of 1422 individuals[81], with about 31% of it being in Mato Grosso state[81]. These numbers, however; were conservative estimates[81]. Similar estimates are urgently required for Pantanal. The rising impact of fires, and particularly from year 2020, signaled a red flag to a supposed stability in the system. Nonetheless, the complex dynamic of fires, floods and vegetation cover in Pantanal may make a similar approach, based mostly on satellite images, more difficult to this biome. Individual jaguars currently being monitored in Pantanal will provide critical information to understand the impact of fires on movement behaviour and habitat selection. Along with that, studies investigating number of dead individuals of different species[22], as well as the consequences to their population size[22], will allow a better understanding of the dimension of the fire impacts.

Conclusion

In order to prevent such catastrophic fires, it is important that central and regional Brazilian government work in unisono with different sectors of civil society[16,39,60,82,83]. As well as it is important to coordinate conservation actions with the neighbors countries within the UPRB (Argentina, Bolivia and Paraguay)[41]. A first and important step is to recognize the risks and use available scientific information (e.g. data, spatial models, forecasts) to build and implement effective plans in time including an Integrated Fire Management program in the Pantanal [16,35,39,60,82,83]. Environmental and wildlife services should be empowered, and designation of funding should be done well in advance to constitute and keep preventive and permanent fire brigades (including indigenous and other local members) in a year-round fire (and restoration) management[16]. Implementation of specific legislation to the Pantanal to regulate activities and account for their impacts, are important to protected the whole Paraguay River Basin[17,56].

Evaluation of the impact of sediments retention and erosion from hydroelectric stations, or from livestock and agriculture activities in the uplands regions, should base and guide measures of control such as restoration of riparian vegetation and reduction in the numbers of hydropower stations [19,39,41,57,58,60,64]. Possible location choices should consider the impacts on fish movement, reproduction and survival (at different stages); as well as the economic importance of the different types of fishing activities (commercial, occasional or touristic)[60]. Technical solutions are also viable, the last station downstream for instance, could be integrated with others upstream and regulate the water flow to make it closer of natural flow conditions and minimize hydropeaking (intra-day oscillations related with energy consumption rates)[60,84,85]. Implementation of these measures, along with reforestation and maintenance of riparian vegetation, may diminish hydrological changes, regulate total amount of sediments thrown in the rivers and alleviate drought effects (Fig.4).

Considering that criminal or uncontrolled use of fire (e.g. for clearing pastures and burn garbage, among others) were the source of majority of fires[12,13,16–20], an intensive educative campaign with a clear message advocating against the use of fires, prohibiting it in dry conditions, and accompanied of inspections and legal punishment could minimize the ignition and their subsequent uncontrolled spread. Furthermore, despite fire's human origin, the major impacts happened in natural areas. Therefore, a strategy addressing protection of PAs and private areas with higher conservation value should be put in place. Part of a successful strategy to protect PAs and other native areas require a collaborative work between wildlife services, government, NGOs and in particular with farmers, which may be neighbors of PA or contain private reserves in their lands. Conversely, such approach would protect people and their property as well.

Strategies focusing on sustainable use have been advocated as the pillar for conservation in Pantanal, particularly because the biome characteristics which allow co-occurrence of cattle livestock in natural areas[39,86,87]. And more recently with the growing importance of Ecotourism[19,88]. There are risks; however, in rely on sustainable use as a major single strategy to more than 96% of the biome. And the exposition to human originated fires is among them. But poaching, conversion of natural grasses to exotic pastures and other human impacts are facilitated outside PAs. Furthermore, the current range of Pantanal PAs are not sufficient to effectively protect jaguar populations[47,89]. Hence, augment in PAs of integral protection in number and area is required as a complementary approach to secure higher percentages of this important biome being preserved under minimal human disturb[39,57]. Furthermore, a careful implementation of buffer zones around current, and possibly future PA of integral protection, would mitigate risk of fire and other human impacts (e.g. firebreaks). A mixed approach, targeting good practices of sustainable use in private areas (e.g. keeping natural pastures to cattle), and on the other hand increasing integral PA percentage at least to the minimum of 17% recommended by the Aichi goals for terrestrial ecosystems[39,57], would target different conservation needs[39] and enhance protection of several species .

Pantanal is drying and dying. A sequence of severe droughts in the UPRB have reduced the Pantanal's characteristic seasonal flood pulse, its "heart beat". Which also have reduced the apport of nutrients to the floodplains and affected the entire Pantanal biodiversity communities. The 2020's destructive fires ravaged a biome already weakened by the drought. Besides, several human activities provoke a positive feedback contributing to drought and fires. Inobtrusive cumulative anthropic impacts and careless use of natural resources could be comparable to an invisible, slow but deadly virus. If on one hand the isolation of any deleterious impact would be the most guaranteed strategy for conservation, on the other hand, sustainable use, could be analogous to a vaccine. In other words, the impacts need to be mitigated to a point in which the uses and the damages caused are still sustainable. While heat and drought from climate predictions cannot be prevented at this time, acting now may mitigate climate change in the future. On top of that, immediate management can only be done controlling human impacts. Funding is the oxygen required to have trained personal ready before fire season start again. Lack of "oxygen" (funding) and denial of the "vaccine' (sustainable use) will put Pantanal in a perverse vortex (positive feedback of cumulative impacts, Fig.4).

Threatened by Global warming and rapid anthropogenic changes, the Pantanal (the largest wetland in the World, a biodiversity hotspot, Ramsar and World Heritage Site[39,82]) requires synergistic strategies for fighting wildfires and promote maintenance of critical habitats, survival of jaguars and species under their umbrella, as well as human safety and climate change mitigation.

Methods

Study area:

The Pantanal is the largest wetland in the World[39,57] and is characterized by a mosaic landscape with floodable and non-floodable areas containing grasslands, forests, open woodlands and temporary or permanent aquatic habitats[29,39,43,68]. The Pantanal wetland is located within the Upper Paraguay River Basin with 600,000 km2 in total and 362,376 km2 in Brazil [90], encompassing 179,300 km2 across Brazil (78%), Bolivia (18%), and Paraguay (4%)[39]. UPRB contains the springs of rivers which drain to lowlands, flooding in Pantanal[57]. Wet and dry seasons are clearly marked, with November to March receiving the majority of yearly rain and defining a seasonal flood pulse[39,91] which controls and shapes the biota in the canal-plain system[61,91]. The water drained from the plateaus in the rainy seasons are stored in the Pantanal wetlands which deliver it slowly downstream, to the Paraguay River[35]. In its turn the seasonal floods impact on nutrient cycling, vegetation, primary productivity and wildlife[92]. Along with floods, fire is another element which interfere in species abundance and composition[31,32]. While in small amounts fire may promote diversity, recurrence of high intensity fires is likely to create the opposite effect[12,31–33].

Climate, precipitation and temperature differ in time and space along the Pantanal wetlands, as well as along the entire UPBR [36,39,61,65,93,94]. According with the Köppen classification[93] the Upper Paraguay river basin (UPRB) includes mostly Tropical zones with dry winter (Aw) with annual rainfall around 1,400 mm (Pantanal region). It includes as well monsoon (Am) with rainfall between 1,300 and 1,600 mm, a small area in the South considered as without dry season (Af) 1,400 and 1,800 mm, and an even smaller portion classified as a Humid subtropical zone with hot summer (Cfa) [93]. Rainfall volumes are usually higher in the N-NE (near 2000 mm)[61,66] and S (1800 mm)[61], coinciding with the uplands (plateaus). Whereas in central Pantanal volumes are lower, with annual medians near 900 mm/year (and 800 mm near the Bolivian Chaco) [61]. Neighboring biomes biogeographically influence the Pantanal's biodiversity; these are the savanna or Cerrado which covers the surrounding plateaus to the east, Amazonia to the north, the Atlantic Forest to the southeast, represented by semi-deciduous and deciduous forests, and the Chaco to the southwest. The Pantanal is a biodiversity hotspot and was declared a National Heritage Site by the Brazilian Constitution of 1988 and a Biosphere Reserve by UNESCO in 2000[39,82].

Jaguar data and preparation:

Jaguar GPS movement data of 56 individuals monitored in Pantanal came from seven study sites from Brazil and Paraguay, and are freely available[48]. From these, we used 45 individuals classified as residents in Brazilian Pantanal in the main analysis. On top of that, we used other seven individuals, four not residents from Brazil and three residents from Paraguay, in the reference analysis. Jaguar minimal sampling period used was 25 days and the maximum 591 days (SI, datapaper[48]). Data cleaning and preparation checking for complete cases, temporal order and duplicates was done in R[95–97].

Individual residency status was evaluated analyzing the curves of semi-variograms (SI_Fig.S6) [45,89], along with complementary statistics such as animal effective number of range crossings

(Narea or DOFarea) available within the continuous time movement models R package (ctmm)[98,99]. Jaguar movement data fitted better to models that account for residency for all jaguars. But truly resident individuals established and stayed within their home ranges during the monitoring period, which is represented by an asymptote in the semi-variograms[45,89] and DOFarea > 5[100] (SI_Fig.S6).

GIS, rainfall and pluviosity data:

We acquired near real-time (NRT) active fire locations in rasterized form of 1 Km resolution, with one or more fire occurrences within the pixel, through Google Earth Engine[50]. This data was processed by the Land, Atmosphere Near real-time Capability for EOS (LANCE)/ Fire Information for Resource Management System (FIRMS) using the standard MODIS MOD14/MYD14 Fire and Thermal Anomalies product[49,51]. We used fire data from January 2005 to December 31st 2020 in the main analyses. This period corresponds to the jaguar monitoring time (2005 to 2016), but evaluate as well fire impacts on subsequent years. We used both information, the occurrence of fires and their intensity (temperature in Kelvin). We adopted a threshold of 325 Kelvin as a determinant of fire occurrence[49,101]. Therefore, only pixels with fire intensity above this value were assumed as an occurrence of fire.

Spatial limits of Brazilian Pantanal, the Upper Paraguay River Basin and Protected Areas were downloaded from Brazilian Ministry of Environment geodatabase[38]. Estimates of yearly land use change and wetland extension were based on MapBiomas collection 5.0[29]. Precipitation and river water levels used came respectively from [24,25] and [27,28]. We used Federal, State and Municipal Protected Area categories[38] because these categories imply in legal Governmental or private responsibility towards conservation. Some private protected areas may be missing because data is not freely available ([39]).

Analyses:

We evaluated fire impact in Brazilian Pantanal by overlapping raster images of Brazilian Pantanal legal extent and yearly occurrence of fire. These layers were resampled to match the 1 Km resolution and reclassified using R[95]. Brazilian Pantanal legal extent raster was reclassified in a way the sum of their cells totalizes 1, and then multiplied by the raster of occurrence of fire, resulting in a probability of occurrence of fire per pixel. The sum of these cells resulted in an estimated percentual extent of fire impact in Brazilian Pantanal. Estimates of mean fire intensity per year were calculated based on the average value of these pixels within Brazilian Pantanal.

A similar process of resampling and reclassification of raster images was applied to evaluate fire impact within PAs of Brazilian Pantanal. First, we calculated the extent of PAs within Pantanal. Second, the percentual extent of PAs (in Brazilian Pantanal) impacted by fire, i.e. the probability of occurrence of fire per pixel based on the multiplication of Pantanal's PAs raster by the raster of occurrence of fire. Then we calculated the ratio between PAs impacted by fire and total extent of PAs in Brazilian Pantanal.

Finally, we assessed fire impacts within jaguar HRs in Brazilian Pantanal. We calculated individual jaguar HRs using the Autocorrelated Kernel Density Estimator (AKDE), available through the ctmm R package [98,99], in a common grid with fire raster images. Then we estimated the probability mass function, an indication of jaguar intensity of use within the derived AKDEs raster images and multiplied it by the raster images with occurrence of fire. The sum of the resultant probabilities at each pixel returned the extent of individual jaguar HR impacted by fire. Yearly intensity of fire within HRs were calculated averaging the registered values of fire intensity in each pixel. As final steps, we calculated the frequency distribution of jaguars in PAs, i.e. the extent of HR encompassing PAs. Then we estimated the extent of HRs containing PAs with occurrence of fire. To do so, first we multiplied the estimated probability mass function of each jaguar (corresponding to jaguars' intensity of use in AKDE raster images) by the occurrence of PAs; and after we multiplied these two layers by the raster images with occurrence of fire. The main analyses (Fig.2,3) consisted in compare the impact of fire in all resident jaguar HRs over time (2005 to 2020). Whereas the reference analyses compared fire impacts on resident jaguars only in the years they were monitored (SI_Fig.S3).

Complementary information such as precipitation[24,25], river water levels[26,27], land use change and wetland extension, among other data, were either plotted for comparison along with fire impact during this study period or used to subsidize discussion (SI). All datasets used in this analysis were cited in the methods, with other relevant data presented in the supplementary material or cited in the discussion.

Code availability: The main codes used in this study are freely available in the SI material (SI_Scripts) and will be later made available via GitHub.

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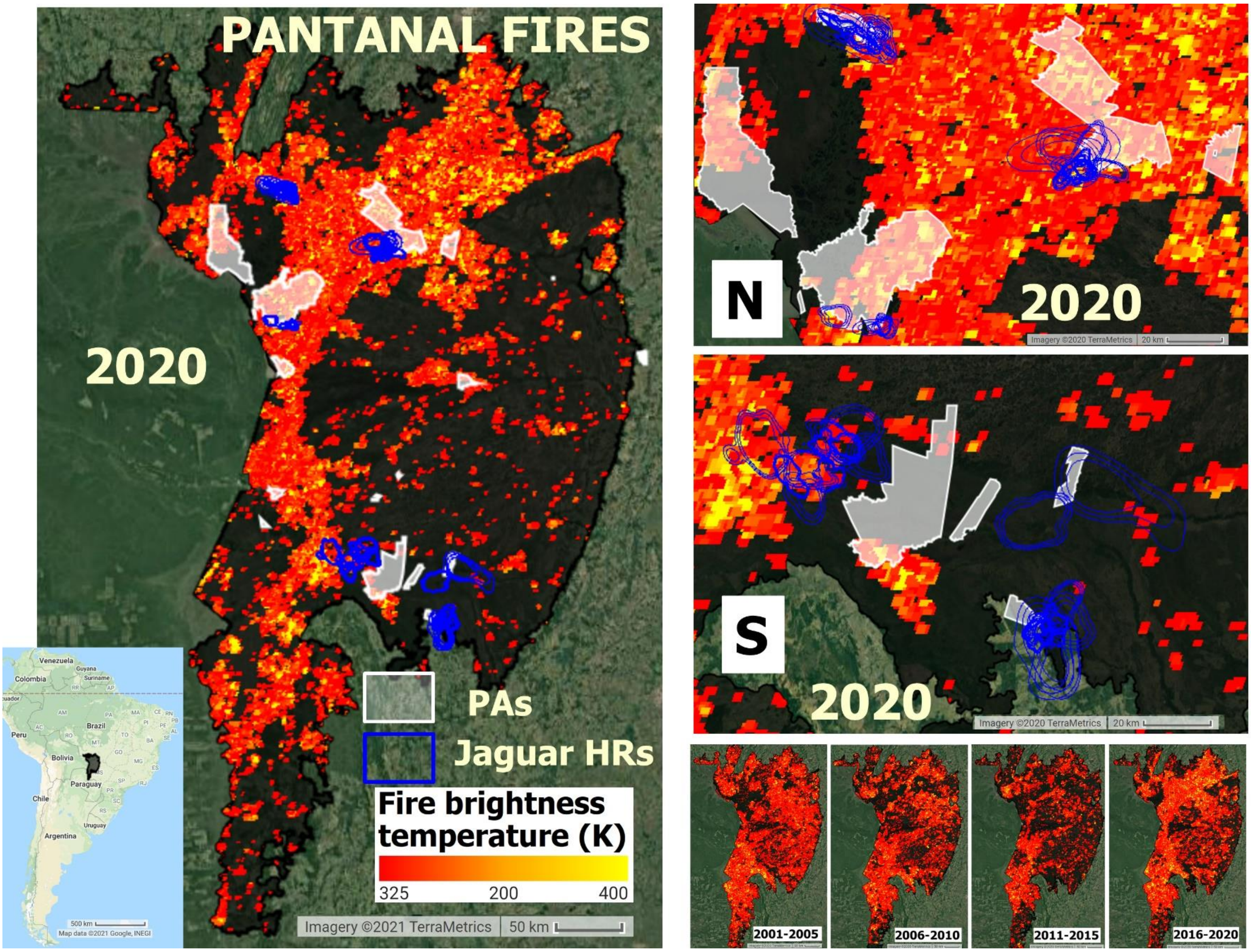

Fig1. Map showing location and occurrence of fires in Brazilian Pantanal in the year of 2020 and the resultant impact on jaguar Home Ranges (HRs) and Protected Areas (PAs) (left). Pantanal North and South are zoomed in detail (top right). Accumulated fires, as well as their intensity, at each 5 years since 2000 (bottom right). Protected Areas are represented in white and home ranges of resident jaguars in blue. Fire occurrence and its correspondent fire brightness temperature are represented in the scale bar from red to yellow (brightest).

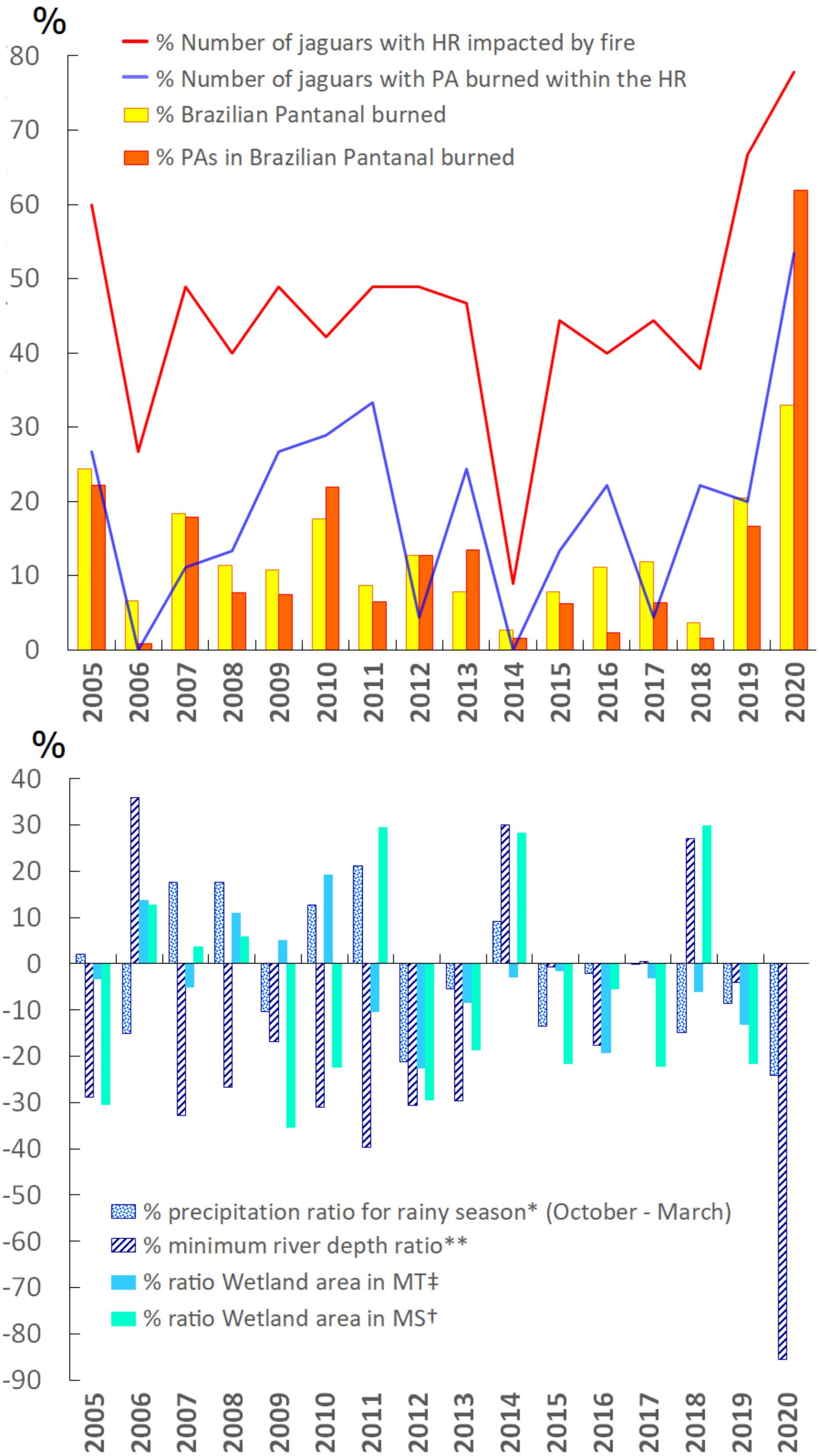

Fig2. Occurrence of fires from year 2005 to 2020 in Brazilian Pantanal. Lines in the top panel show percentage of number of jaguars with occurrence of fire within their home ranges HRs (red) and within Protected Areas PAs (inside HRs, in blue). Histograms show yearly percentage of occurrence fires in Protected areas and in the whole Pantanal. The second panel summarizes percentual changes in precipitation, river depth and wetland flooded areas.

* % precipitation ratio for rainy season (October - March) (rainy season average of monthly medians from 4 stations/average of rainy seasons from multiple years (1967-2019, see SI))
** % minimum river depth ratio (Average of the year minimum river depth from 6 stations/ average (from 6 stations) of the yearly medians of minimuns (1967-2019, see SI)
‡ % ratio Wetland area in MT (Wetland MT annual year area/Average Wetland MT area (1985-2019), see SI)
† % ratio Wetland area in MS (Wetland MS annual year area/Average Wetland MS area (1985-2019), see SI)

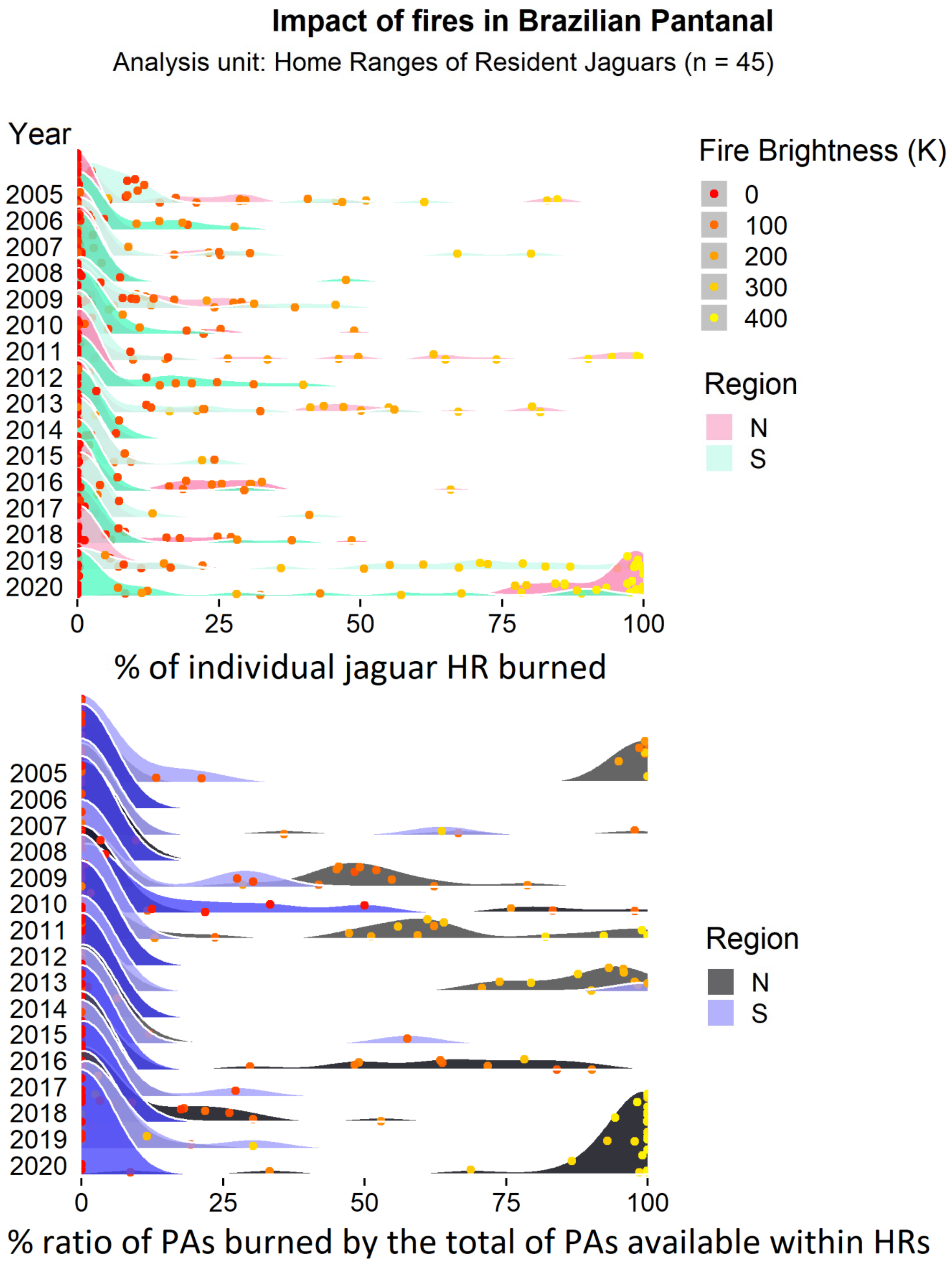

Fig3. Smoothed frequency distributions of annual percentages of fire occurrence in Brazilian Pantanal from 2005 to 2020. Impact of fires in jaguars' home ranges (top panel) and PAs available to jaguars within their HRs (bottom). Points highlight the average temperature intensity (brightness) in Kelvin of each individual for each year.

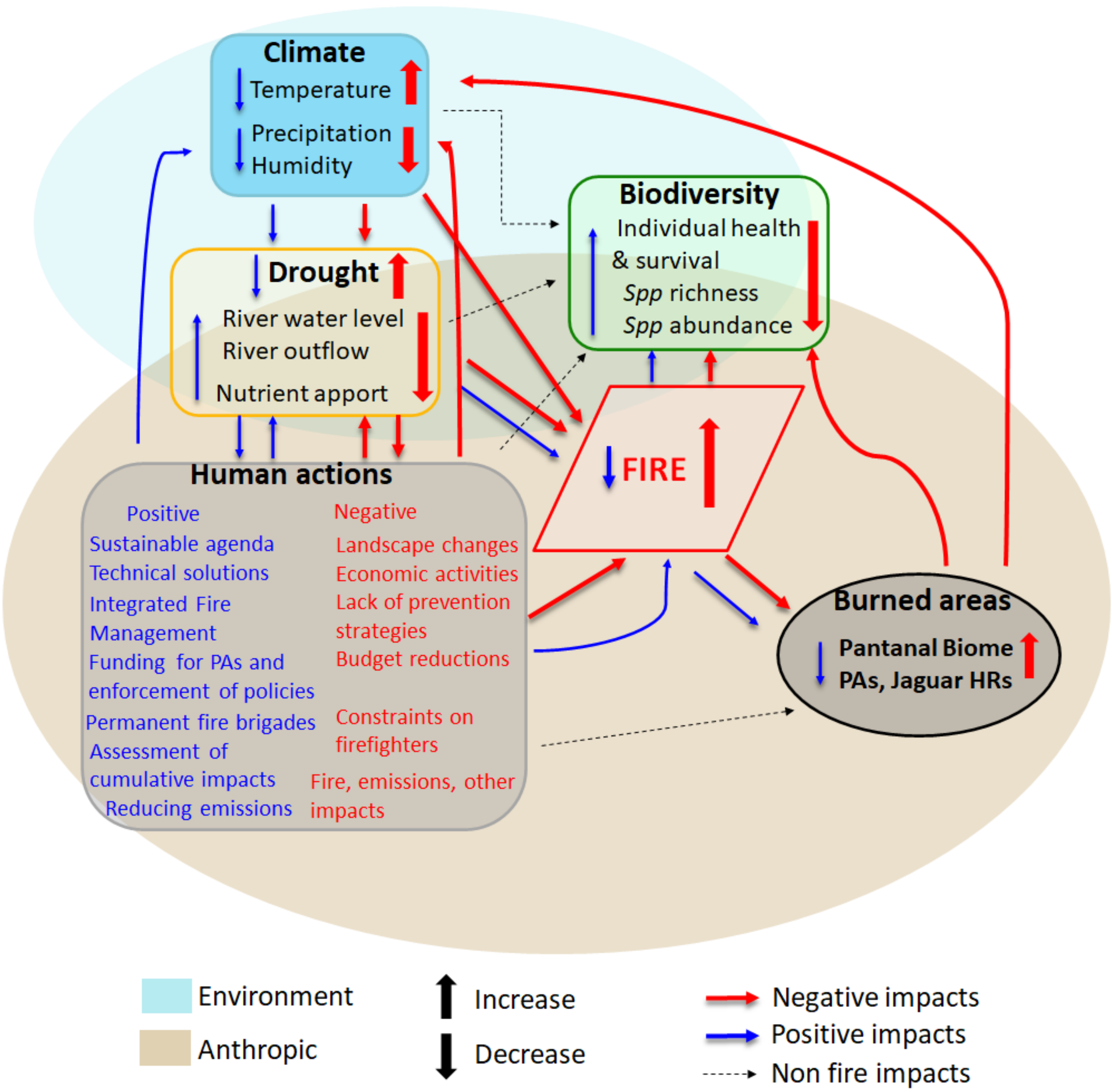

Fig4. Scheme summarizing main fire related impacts occurring in Pantanal. Red arrows are intentionally larger and show a positive feedback linking the increase in human negative impacts, climate change and drought with the increase in fires and burned areas, with consequent negative impact on biodiversity. Blue arrows describe a negative feedback towards fire control and mitigations of impacts. Dashed arrows synthesize other relevant impacts occurring in the biome (e.g. human caused cumulative impacts from infrastructures such as hydroelectricity power plants, river waterways, water and soil pollution from legal and illegal mining and agriculture, poaching and illegal wildlife trade opportunistic exploitation of burned areas; as well as climate natural constrains).

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Supplementary Information

SI_notes

Additional details on results: (Impact of fires in other years, than 2020)

The historical comparison showed clear tendency of increase in fire extension and intensity over the last six years (Figs.1, 2 and 3). Besides 2020's, years of 2019, 2005, 2007, 2010, 2011 and 2013 also deserved some note. During 2019 year the fires consumed 20% of Pantanal and 17% of PAs, mostly in the South part, and affected 67% of resident individuals, in average consuming 21.45% of HR areas (Figs.2,3). In 2005 fires consumed 24.3% of Pantanal and 22,1% of PAs, affected 60% of resident individuals and burned an average of 14% of HR area, with 28.5% of PA burned within them in average (Figs.2,3). Years of 2007 and 2010 had more than 18% of overall Pantanal and PA burned, whereas 2011 and 2013 draw attention due to the impact on jaguars, with average fire occurrence superior to 15% in HRs and to 23% in the PAs within it (Figs.2,3).

Additional details about Impacts in the UPRB and Pantanal

An assessment of level of risk to the integrity of aquatic ecosystems pointed hydropower plants, urbanization and agrobusiness as the three principal stressors among 13 impacting anthropic activities in the UPRB[41]. Environmental degradation (e.g. deforestation, erosion, sewage), economic activities (e.g. agriculture, mining) and infrastructures (e.g. dams, hydropower plants, waterways, gas pipelines) are associated to the demand and pressure of a increasing human population in the UPRB and can interfere in the drainage dynamics, flood pulses and drought extension, consequently impacting the ecological wealth, biodiversity and ecosystem services [19,39,41,57,58,64].

Considering that Pantanal occupies only 38% of the UPRB[68] and that the water which drains to lowlands and flood in Pantanal comes from springs of rivers in the highlands[57,58], the removal of vegetation cover protecting these springs in the neighboring biomes within the UPRB (Cerrado, Amazonia, Atlantic Forest and Chaco) impacts the drainage, water quality and hydrological regimen of the Pantanal[19,41,57,58,68]. Deforestation, along with mining activities[11,39], and hydroelectricity powerplants (Total ≈180, 47 installed or working and 133 planned)[60,102,103] are undeniable causes of changes in water quality and flow, erosion, river sediments[39,57,60,103], reduction of outflow (up to 100% in drier years) and transportation of nutrients to the Pantanal floodplains[60,84,85,103], besides other problems such as reduction of light provoking a decline or disappearance of aquatic plants and algae dependent of photosynthesis[41], hypoxia and a consequent cascade effect, reduction in fruits and seeds as available food to fish[41], and bioaccumulation of toxic mercury[11,104].

Hydroelectricity projects, as well as the implementation of a Paraguayan river waterway, railroads and highways have been debated in the academy, legal courts, and by stakeholders[39,102,105–110]. If big enterprise, such as build the entire 3,440 Km north–south navigable waterway from Cáceres (Brazil) to Nueva Palmira (Uruguay)[39,108,110] or the implementation of large hydroelectric power plant have been barred or reduced, given the preponderant evidence of negative impacts, the subterfuge adopted in many new developments was based on the so called “tyranny of small decisions”[108,111]. This is, in many cases, several small hydroelectricity plants, ports, or relatively short channeling projects have been presented as low impact alternatives without consider their cumulative impacts[112]. In addition, the supposed small individual impact is often used as an excuse to limit the decision-making to a short group of stakeholders[108]. The impact of cumulative effects of small ventures can be avoided only by adopting an holistic perspective in a participatory process engaging scientists with different expertise, along with planers, politicians and other social actors[108,111], in studies of deep content, impartial evaluation, and discussions (e.g. using a Strategic (or Integrated) Environmental Assessments (SEA) or equivalent approaches [113,114]).

Given the environmental and socio-economical complexities of Pantanal and the multiple interests in favor or against development projects, the proposal of studies towards SEA’s direction, seeking to account for the summatory of impacts happening in parts or in the entire Upper Paraguay basin started almost two decades ago[113,115]. Successful regulation based on laws[17] and implementation of update SEAs for Pantanal[41,60,102,110], through a transparent and plural engagement of civil society, could bring unvaluable advances for conservation and provide science-based guidance to attain sustainability[39,41,60,102,110]. Challenging; however, is how to demonstrate and convince decision-makers and citizens’ organizations, which are often driven by immediate economic benefits and developmentalist[116], of SEA value if it occurs in unregulated contexts[114], such as is the case for Pantanal[17,20,56,59,82].

SI_Scripts

A) We plan to make the basic movement data cleaning and preparation scripts available through GitHub soon, but we basically follow J. Fieberg and J. Signer [95–97].

Jaguar Home Range analyses followed Fleming et al.[98,99]

B) Google Earth Engine sample

Run AKDE Home Ranges in R first to enter all of them in GEE and merge them!

```
//// Example
///////////////////////////////////////////////////////////////////////
var J12akde = ee.FeatureCollection("users/alanusp/J12UDakde");

///////////////////////////////////////////////////////////////////////
/////     RESIDENTS PANTANAL
// RESIDENTS AKDEs home ranges
var RESIDENTS = J13akde.merge(J15akde).merge(J18akde).merge(J19akde)
.merge(J22akde).merge(J25akde).merge(J27akde).merge(J28akde).merge(J29akde)
.merge(J30akde).merge(J31akde).merge(J32akde).merge(J33akde).merge(J41akde).merge(J52akde)
.merge(J53akde).merge(J54akde).merge(J55akde).merge(J56akde).merge(J59akde)
.merge(J60akde).merge(J61akde).merge(J68akde).merge(J69akde).merge(J79akde).merge(J84akde)
.merge(J86akde).merge(J87akde).merge(J88akde).merge(J91akde).merge(J92akde).merge(J101akde)
.merge(J104akde).merge(J105akde).merge(J106akde).merge(J107akde).merge(J108akde)
.merge(J109akde).merge(J110akde).merge(J111akde).merge(J112akde)
.merge(J113akde).merge(J115akde).merge(J116akde).merge(J117akde);
////////////////////////////////////////////////////////////////////////

var PantanalBound = ee.Image("users/alanusp/Pantanal2019"),
    PantanalBR = ee.FeatureCollection("users/alanusp/PantanalBR"),
    PantanalBiomeBR = ee.Image("users/alanusp/PantanalBiomeBR"),
    RESIDENT_BR_PA = ee.Image("users/alanusp/RESIDENT_BR_PA"),
    NR_BR_PA = ee.Image("users/alanusp/NR_BR_PA"),
    JPant_PY_PA = ee.Image("users/alanusp/JPant_PY_PA"),
    PantanalPoly_PA = ee.Image("users/alanusp/PantanalPoly_PA"),
    UCs = ee.FeatureCollection("users/alanusp/UCs"),
```

```
    geometry =
    /* color: #d63000 */
    /* displayProperties: [
      {
        "type": "rectangle"
      }
    ] */
    ee.Geometry.Polygon(
        [[[-59.20858336397284, -15.494493396964149],
          [-59.20858336397284, -22.246950530191828],
          [-54.68221617647284, -22.246950530191828],
          [-54.68221617647284, -15.494493396964149]]], null, false);
//////////////////////////////////////////////////////////////////////
///////     2020      //////////////////////////////////
var firedata2020 = ee.ImageCollection('FIRMS').filter(
    ee.Filter.date('2020-01-01','2020-12-31')); //// database is usually 3 days behind
//var firedata2020 = firedata2020.filterMetadata('confidence','greater_than',90);
var fires2020 = firedata2020.select('T21');
Map.addLayer(firedata2020, {}, 'firedata2020', false);

var firesVis = {
  min: 325.0,
  max: 400.0,
  palette: ['red', 'orange', 'yellow'],
};

Map.centerObject(PantanalBR);
Map.addLayer(fires2020, firesVis, 'Fires',false);
Map.addLayer(PantanalBR,{},"PantanalBR",false);
print(PantanalBR);

///////   ImageCollecton to Image
// PantanalBR
var PantanalBRFire2020_Max = PantanalBRFire2020.reduce(ee.Reducer.max()).toFloat();
var PantanalBRFire1 = PantanalBRFire2020_Max.gt(325).unmask(0).toFloat();
//var PantanalBRFire2020_Max = PantanalBRFire2020_Max.gt(325);            /////////
// Make an image out of the CD_Bioma attribute.
var PantanalBRr = PantanalBR
  .filter(ee.Filter.notNull(['CD_Bioma']))
 .reduceToImage({
  properties: ['CD_Bioma'],
  reducer: ee.Reducer.first()
}); //.clip(PantanalBR);
//Map.addLayer(PantanalBRr,{},"PantanalBRr",false);

print(PantanalBRr,'PantanalBRr')
//PantanalBRr  Raster
// Export, 1Km resolution

Map.addLayer(PantanalBiomeBR,{},"PantanalBiomeBR",false);
//print(PantanalBiomeBR,'PantanalBiomeBR')

//Export.image.toDrive({
  //image: PantanalBiomeBR,
  //description:'PantanalBiomeBR',
  //folder:'GEE',
  //fileNamePrefix:'PantanalBiomeBR',
  //region:PantanalBRr,
  //scale:1000,
  //crs: 'EPSG:32721',
  //maxPixels: 1e12,
  //fileFormat:'GeoTIFF'
//});


// PantanalPoly
var PantanalFire2020_Max = PantanalFire2020.reduce(ee.Reducer.max());
//var PantanalFire2020_Max = PantanalFire2020_Max.gt(325)                 /////////
Map.addLayer(PantanalFire2020_Max, firesVis,'PantanalFire2020_Max');
print(PantanalFire2020_Max)
//var PantanalFire2020_Med = PantanalFire2020.reduce(ee.Reducer.median());

// Mask out pixels
var PantanalFire1 = PantanalFire2020_Max.gt(325).unmask(0);
var VIS_FIRE_MASK = { palette: ['white','purple']};
Map.addLayer(PantanalFire1, VIS_FIRE_MASK, 'PantanalFire1',false);
//print(PantanalFire1,"PantanalFire1")
//var PantanalFire2 = PantanalFire2020_Med.gt(325).unmask(0);
//var VIS_FIRE_MASK2 = { palette: ['white','blue']};
//Map.addLayer(PantanalFire2, VIS_FIRE_MASK2, 'PantanalFire2',false);
//var PantanalFirePoly = fire1.filterBounds(PantanalPoly).map(function(image){return
image.clip(PantanalPoly)});

//var VIS_FIRE_MASK = { palette: ['white','red']};
//var J20water1 = J20occurrence.gt(0).unmask(0);

//// Export 1000m resolution
Export.image.toDrive({
```

```
  image: PantanalFire2020_Max,
  description:'PantanalFire2020_Max_1Km',
  folder:'GEE',
  fileNamePrefix:'PantanalFire2020_Max_1Km',
  //region:PantanalPoly,
  scale:1000,
  crs: 'EPSG:32721',
  maxPixels: 1e12,
  fileFormat:'GeoTIFF'
});
//// Export 1000m resolution
Export.image.toDrive({
  image: PantanalFire1,
  description:'PantanalFire1_2020_1Km',
  folder:'GEE',
  fileNamePrefix:'PantanalFire1_2020_1Km',
  //region:PantanalPoly,
  scale:1000,
  crs: 'EPSG:32721',
  maxPixels: 1e12,
  fileFormat:'GeoTIFF'
});
//Map.addLayer(J13akde,{palette:['white','blue']},"J13akde",true);
var UCsPantanal = ee.FeatureCollection('users/alanusp/UCs').filterBounds(PantanalBR);
// Set a new property.
UCsPantanal = UCsPantanal.set('presence', 1);

Map.addLayer(UCsPantanal,{color:'white'},'UCsPantanal');
print(UCsPantanal,'UCsPantanal');


// Create an empty image into which to paint the features, cast to byte.
var empty = ee.Image().byte();

// Paint all the polygon edges with the same number and width, display.
var outlineNR = empty.paint({
  featureCollection: NR,
  color: 1,
  width: 1
});
Map.addLayer(outlineNR, {palette: '#800080'}, 'NR');
//Map.addLayer(NR,{color: '#800080'},"NR",true);   //// purple

Map.addLayer(Py,{color:"#f5a8bb"},"Py",true);   ////  light salmon


// Paint all the polygon edges with the same number and width, display.
var outlineRes = empty.paint({
  featureCollection: RESIDENTS,
  color: 1,
  width: 1
});
Map.addLayer(outlineRes, {palette: '#0000ff'}, 'RESIDENTS');
//Map.addLayer(RESIDENTS,{color:"#0000ff"},"RESIDENTS",true);  //// blue


// Export the FeatureCollection to a shp file.
Export.table.toDrive({
 collection: RESIDENTS,
 //region:RANGE,
description:'RESIDENTS',
fileFormat: 'SHP'});

///////////////////////////////////////////////////////////////

/*
 * Legend setup
 */

// Creates a color bar thumbnail image for use in legend from the given color
// palette.
function makeColorBarParams(palette) {
  return {
    bbox: [0, 0, 1, 0.1],
    dimensions: '100x10',
    format: 'png',
    min: 0,
    max: 1,
    palette: palette,
  };
}

// Create the color bar for the legend.
var colorBar = ui.Thumbnail({
  image: ee.Image.pixelLonLat().select(0),
  params: makeColorBarParams(firesVis.palette),
  style: {stretch: 'horizontal', margin: '0px 8px', maxHeight: '24px'},
});
```

```
// Create a panel with three numbers for the legend.
var legendLabels = ui.Panel({
  widgets: [
    ui.Label(firesVis.min, {margin: '4px 8px'}),
    ui.Label(
        (firesVis.max / 2),
        {margin: '4px 8px', textAlign: 'center', stretch: 'horizontal'}),
    ui.Label(firesVis.max, {margin: '4px 8px'})
  ],
  layout: ui.Panel.Layout.flow('horizontal')
});

var legendTitle = ui.Label({
  value: 'Fire brightness temperature (K)',
  style: {fontWeight: 'bold'}
});

// Add the legendPanel to the map.
var legendPanel = ui.Panel([legendTitle, colorBar, legendLabels]);
Map.add(legendPanel);
```

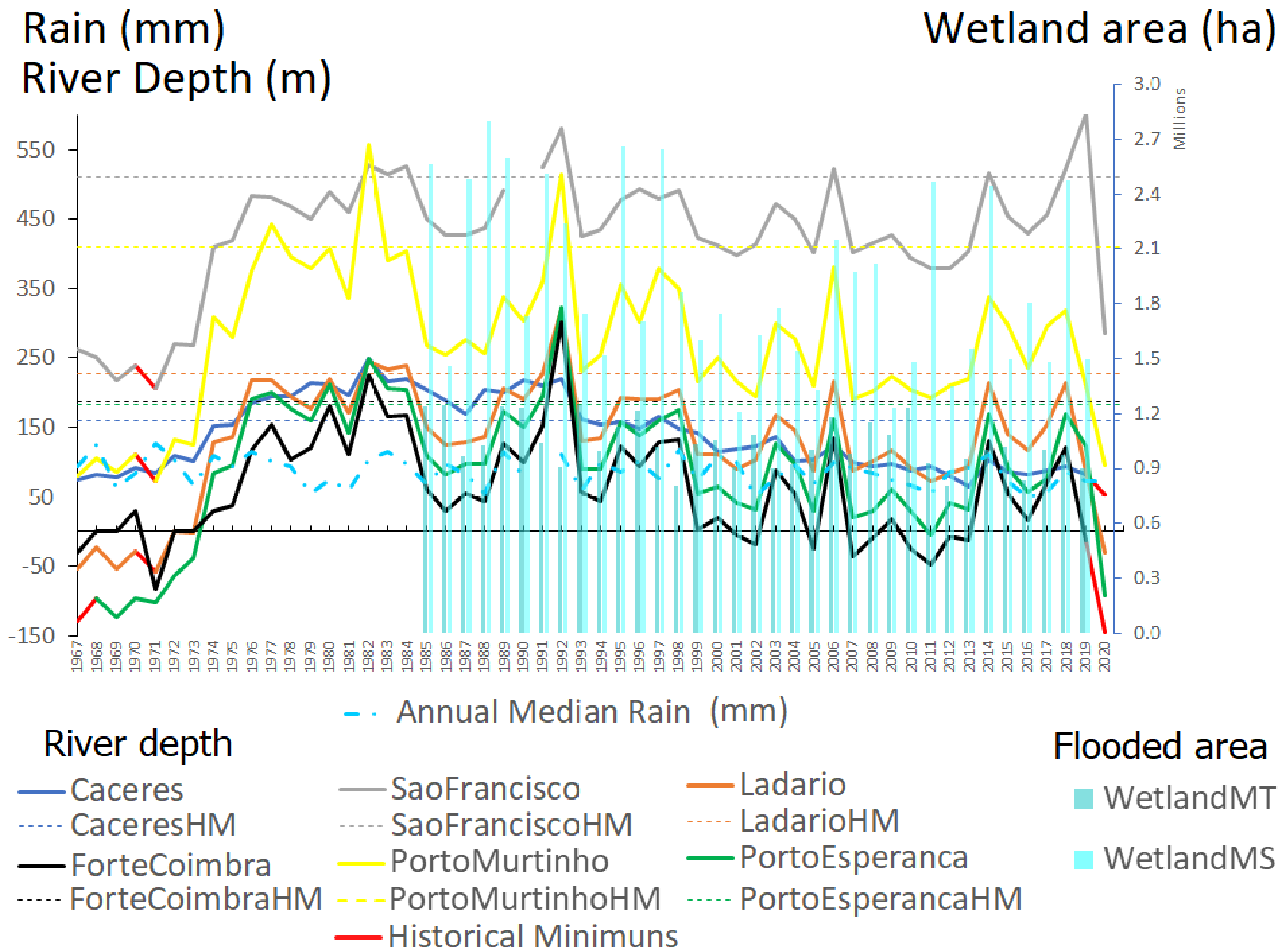
C) R ctmm package used for HR calculation and raster operations with fire

```
#'
#' #  **FIRE and JAGUAR HOME RANGES**
#'
#' #### **Alan Eduardo de Barros**
#' date: "January, 10 2021"
#'
#' Run jaguardataprep first!!!
#'
#' #### Install
#install.packages("dplyr")
#install.packages("amt")
#install.packages("ctmm")
library(ctmm)
#library(dplyr)
#library(amt)
#'
#' #### Make some memory available to R
# In the Windows command line prompt:cd C:\  and  cd Program Files\R\R-4.0.2\bin\x64 and then:
Rgui.exe --max-ppsize=500000
# Then in R:
options("expressions"=500000); memory.limit(500000)
gc()
#'
####################################################################################################
###############
#'

#'##    **FIRE IMPACT IN BRAZILIAN PANTANAL**
#'
#'###       **FIRE OCCURRENCE**

#' #### Exploring Fire Impact at whole Brazilian Pantanal first!!!
### Brazilian Pantanal extent in raster  (1Km resolution)
PantanalBiomeBR<- "E:/GIS/Fire/PantanalBiomeBR.tif"
PantanalBiomeBRr <- raster(PantanalBiomeBR)

### PantanalBRFire1_2020_1Km
PantanalBRFire1<- "E:/GIS/Fire/PantanalBRFire1_2020_1Km.tif"
PantanalBRFire1R<- raster(PantanalBRFire1)
table(values(PantanalBRFire1R))
#'
#'#### Resample
PantR<-resample(PantanalBiomeBRr,PantanalBRFire1R,method="ngb")
table(values(PantR))
cellStats(PantR,'sum')
1/(cellStats(PantR,'sum'))
# 6.627257e-06
#'####  Reclassifying Pantanal BR raster (in a way the sum totalizes 1)
#Pantanal1 = c("0","1")
Pantanal1R <- subs(PantR, data.frame(id=c(1),class=c(1/(cellStats(PantR,'sum')))))
cellStats(Pantanal1R,'sum')
writeRaster(Pantanal1R,filename=file.path("E:/GIS/Fire/Pantanal1R."), format="GTiff", overwrite=TRUE)
Pantanal1<- "E:/GIS/Fire/Pantanal1R.tif"
Pantanal1R <- raster(Pantanal1)
#'
#' ### Extent of Brazilian Pantanal impacted by fire (expectation %)
PantanalBRFprob1<-(Pantanal1R*PantanalBRFire1R)
```

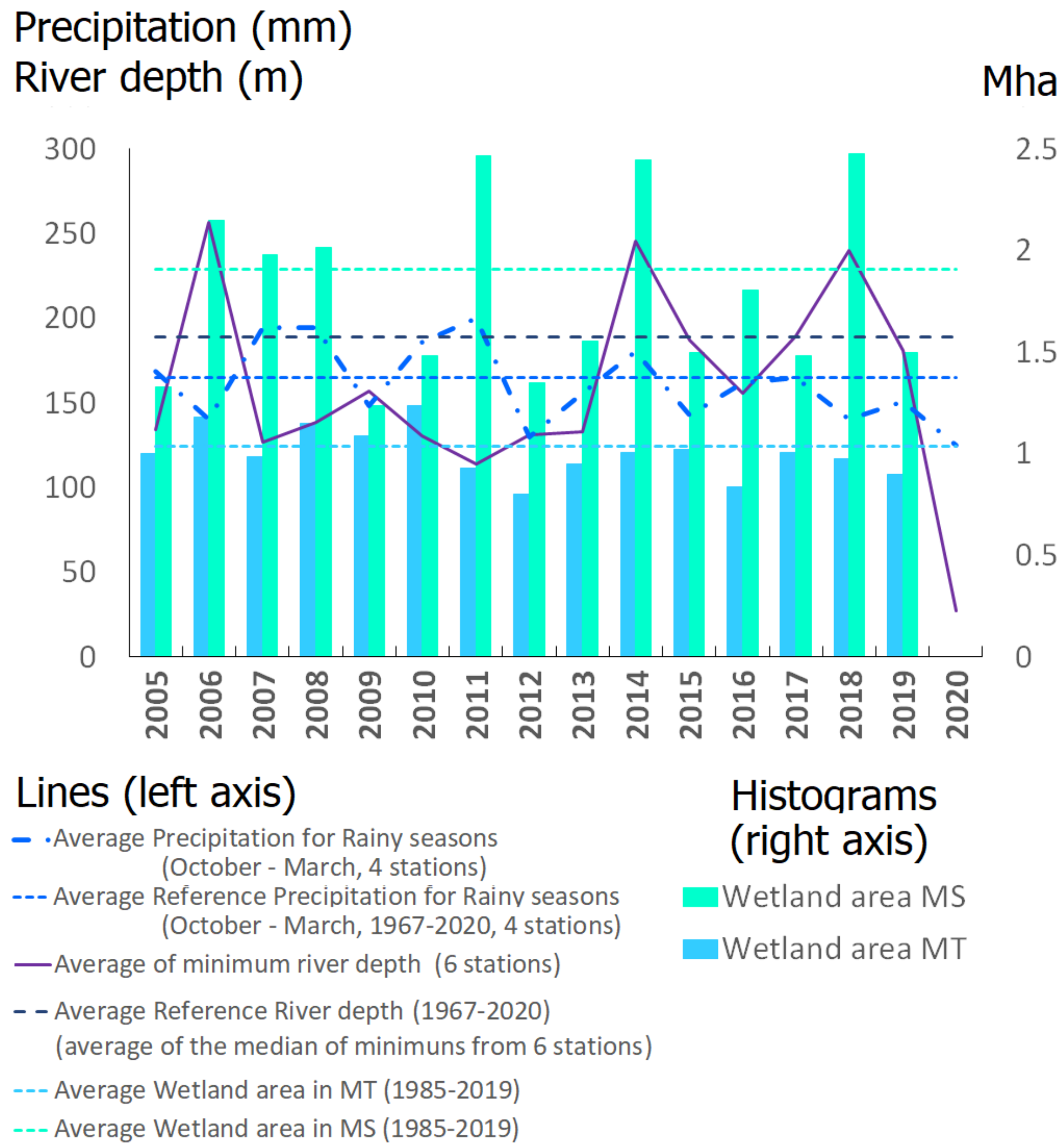
```
#' sum(PantanalFire1R*raster(UDakdeJ13,DF="PMF"))
(FirePantanalBR<-cellStats(PantanalBRFprob1,'sum'))
#'
#'

#'###                **FIRE INTENSITY**

#' PantanalBRFire2020_Max_1Km
PantanalBRFire2020_Max_1Km<- "E:/GIS/Fire/PantanalBRFire2020_Max_1Km.tif"
PantanalBRFire2020_Max_1KmR<- raster(PantanalBRFire2020_Max_1Km)
hist(values(PantanalBRFire2020_Max_1KmR))
abline(v=325,col="red")   ### 325 K was the threshold adopted
summary(values(PantanalBRFire2020_Max_1KmR))
cellStats(PantanalBRFire2020_Max_1KmR,'mean')
#'
#'
#########################################################################################################################
#' ##          **BRAZILIAN PANTANAL STATISTICS 2020**
#'
#' ####  % Cover burned in BRAZILIAN PANTANAL
(FirePantanalBR2020<-cellStats(PantanalBRFprob1,'sum'))
#wite.table(FirePantanalBR2020,file="E:/GIS/Fire/FirePantanalBR2020.txt",row.names =
F,quote=F,col.names=T,sep="\t")
write_rds(FirePantanalBR2020, "E:/GIS/Fire/FirePantanalBR2020.rds")
(FirePantanalBR2020<- readRDS("E:/GIS/Fire/FirePantanalBR2020.rds"))

#' ####    Average Intensity
(IntensityPantanalBR2020 <- cellStats(PantanalBRFire2020_Max_1KmR,'mean'))
write_rds(IntensityPantanalBR2020, "E:/GIS/Fire/IntensityPantanalBR2020.rds")
(IntensityPantanalBR2020<- readRDS("E:/GIS/Fire/IntensityPantanalBR2020.rds"))
##########################################################################################################################

#'
#'
#'###          **Protected Areas/ UCs  BR**
#'
## PantanalBR_PA <- "E:/GIS/Fire/PantanalBR_PA.tif"
PantanalBR_PA <- "E:/GIS/Fire/UCsPantanal1.tif"
PantanalBR_PAr <- raster(PantanalBR_PA)
#'#### Resample
PantanalBR_PAr<-resample(PantanalBR_PAr,Pantanal1R,method="ngb")
table(values(PantanalBR_PAr))
(PantanalBR_PA_SUM<-cellStats(PantanalBR_PAr,'sum'))
#'
#' ###        **Pantanal PA STATISTICS 2020**
#' ### 1) Extent of PAs within Brazilian Pantanal
PAPantanalBR<-(Pantanal1R*PantanalBR_PAr)
(PAPantanalBR_SUM<-cellStats(PAPantanalBR,'sum'))
write_rds(PAPantanalBR_SUM, "E:/GIS/Fire/PAPantanal.rds")
(PAPantanal<- readRDS("E:/GIS/Fire/PAPantanal.rds"))
#'
#' ### 2) Extent of PAs in Brazilian Pantanal impacted by fire (expectation %)
PantanalBR_FirePAprob1<-(PAPantanalBR*PantanalBRFire1R)
(PantanalBR_FirePA<-cellStats(PantanalBR_FirePAprob1,'sum'))
write_rds(PantanalBR_FirePA, "E:/GIS/Fire/PAPantanalFire.rds")
(PAPantanalFire<- readRDS("E:/GIS/Fire/PAPantanalFire.rds"))
#'
#' ### 3) Ratio of Extent of PAs in Brazilian Pantanal impacted by fire / by the Total Extent of PAs
within Brazilian Pantanal
(FireRatioPA<-PantanalBR_FirePA/PAPantanalBR_SUM)
write_rds(FireRatioPA, "E:/GIS/Fire/FireRatioPA.rds")
(FireRatioPA<- readRDS("E:/GIS/Fire/FireRatioPA.rds"))
#'
#'
#########################################################################################################################

#'
#'##    **FIRE IMPACTS WITHIN JAGUAR HOME RANGES IN BRAZILIAN PANTANAL**
#'
#' #### Exploring Fire Impact on Pantanal's jaguars (rasters based on  70km buffer polygons and
AKDEs)
#PantanalFire1_2020_1Km
PantanalFire1<- "E:/GIS/Fire/PantanalFire1_2020_1Km.tif"    ###  Polygons
#PantanalFire1<- "E:/GIS/Fire/PantanalFire1_100.tif"
PantanalFire1R<- raster(PantanalFire1)
#PantanalFire2020_Max_1Km
PantanalFire2020_Max<- "E:/GIS/Fire/PantanalFire2020_Max_1Km.tif"
#PantanalFire2020_Max<- "E:/GIS/Fire/PantanalFire2020_Max_100.tif"
PantanalFire2020_MaxR<- raster(PantanalFire2020_Max)
#'
#'

############    EXAMPLE WITH ONE INDIVIDUAL JAGUAR
######################################################################
#' #### J13
```

```
J13trk
#J13ctmm <- as_telemetry(J13trk)
J13move <- as_move(J13trk)
J13ctmm <- as.telemetry(J13move)
#J13ctmm <- projection(J13trk)
GUESS <- ctmm.guess(J13ctmm,interactive=FALSE)
FIT <- ctmm.fit(J13ctmm,GUESS)
projection(J13ctmm)
#'
#'####  **Occurrence of FIRE (1Km Resolution)**
### Occurrence PantanalFire1R
UDakdeJ13 <- akde(J13ctmm,FIT,grid=PantanalFire1R);summary(UDakdeJ13)  # calculate the AKDE HR in a common grid with fire
projection(UDakdeJ13)
# raster(AKDE)
UDakdeJ13R<-raster(UDakdeJ13,DF="PMF")
cellStats(UDakdeJ13R,'sum')   ### Just to check AKDE home range sum
# raster Fire1
cellStats(PantanalFire1R,'sum')  ### Just to check Fire1 (occurrence) sum
#'
#' #### Extent of HR impacted by fire (expectation %)
J13Fprob1<-(UDakdeJ13R*PantanalFire1R)
#sum(PantanalFire1R*raster(UDakdeJ13,DF="PMF"))
(FJ13<-cellStats(J13Fprob1,'sum'))
#'

#'####  **Max Fires 1Km Resolution**
### PantanalFire2020_Max
UDakdeJ13Max <- akde(J13ctmm,FIT,grid=PantanalFire2020_MaxR);summary(UDakdeJ13Max)  # calculate the AKDE HR in a common grid with fire
projection(UDakdeJ13Max)
# raster(AKDE)
UDakdeJ13MaxR<-raster(UDakdeJ13Max,DF="PMF")
#table(as.data.frame(UDakdeJ13MaxR))
cellStats(UDakdeJ13MaxR,'sum')   ### Just to check AKDE home range sum
# raster FireMax
#table(as.data.frame(PantanalFire2020_MaxR))
cellStats(PantanalFire2020_MaxR,'mean')  ### Just to check
summary(values(PantanalFire2020_MaxR))
hist(values(PantanalFire2020_MaxR))
abline(v=325,col="red")   ### 325 K was the threshold adopted
#'
#'#### Intensity of fire impact
J13FprobMax<-(UDakdeJ13MaxR*PantanalFire2020_MaxR)
(FJ13Max<-cellStats(J13FprobMax,'sum'))
#'

#'####  **PROTECTED AREAS, JAGUARS AND FIRE**
#'
#' #### 1) Frequence of jaguars in PAs
summary(UDakdeJ13)
#'
#' #### Extent of HR encompassing PAs (Frequence distribution of jaguars in PAs )
J13PAprob1<-(UDakdeJ13R*PantanalBR_PAr);J13PAprob1
(PAJ13<-cellStats(J13PAprob1,'sum'))
#'
#' #' #### 2)Extent of HR containing PAs with occurrence of fire (expectation %)
J13FPAprob1<-(UDakdeJ13R*PantanalBR_PAr*PantanalFire1R)
(FPAJ13<-cellStats(J13FPAprob1,'sum'))
#'

#write_rds(J13Fprob1, "E:/GIS/Fire/J13Fprob1.rds")
#(J13Fprob1<- readRDS("E:/GIS/Fire/J13Fprob1.rds"))
write_rds(FJ13, "E:/GIS/Fire/FJ13.rds")
(FJ13<- readRDS("E:/GIS/Fire/FJ13.rds"))
#write_rds(J13FprobMax, "E:/GIS/Fire/J13FprobMax.rds")
#(J13FprobMax<- readRDS("E:/GIS/Fire/J13FprobMax.rds"))
write_rds(FJ13Max, "E:/GIS/Fire/FJ13Max.rds")
(FJ13Max<- readRDS("E:/GIS/Fire/FJ13Max.rds"))
write_rds(PAJ13, "E:/GIS/Fire/PAJ13.rds")
(PAJ13<- readRDS("E:/GIS/Fire/PAJ13.rds"))
write_rds(FPAJ13, "E:/GIS/Fire/FPAJ13.rds")
(FPAJ13<- readRDS("E:/GIS/Fire/FPAJ13.rds"))

#save.image(file="JFire.RData")
#load(file="JFire.RData")
```

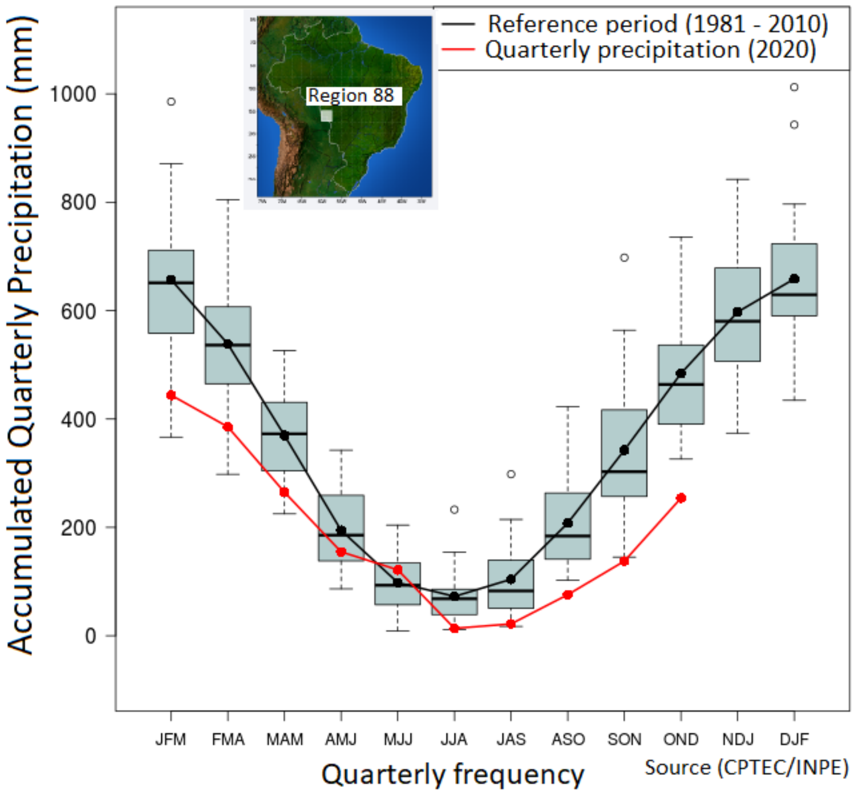
SI_Figures



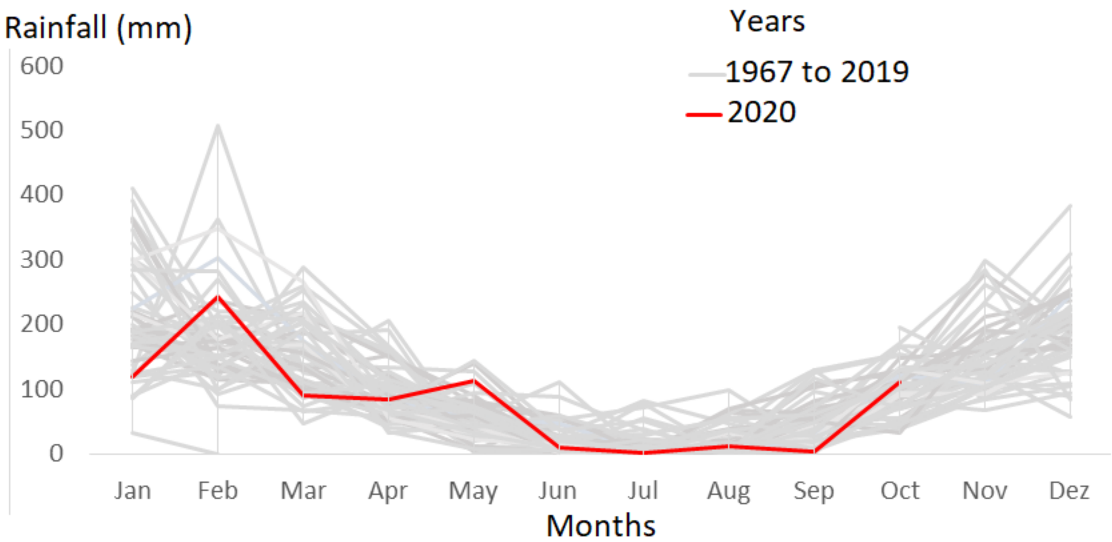
Fig_S1a. Continuous lines correspond to yearly minimum river water depths (minimum quotas in meters from 1967 to 2020) at six Pantanal gauge stations in the Paraguay River. Dashed lines in the same colors correspond to the respective historical medians (HM) at each station [27]. Histograms correspond to the MapBiomas yearly wetland estimated area (ha) in Pantanal areas of Mato Grosso (MT) and Mato Grosso do Sul (MS) from1985 to 2019[29]. Dashed-dotted line correspond to Annual Median Rain (reference 1967 to 2019).



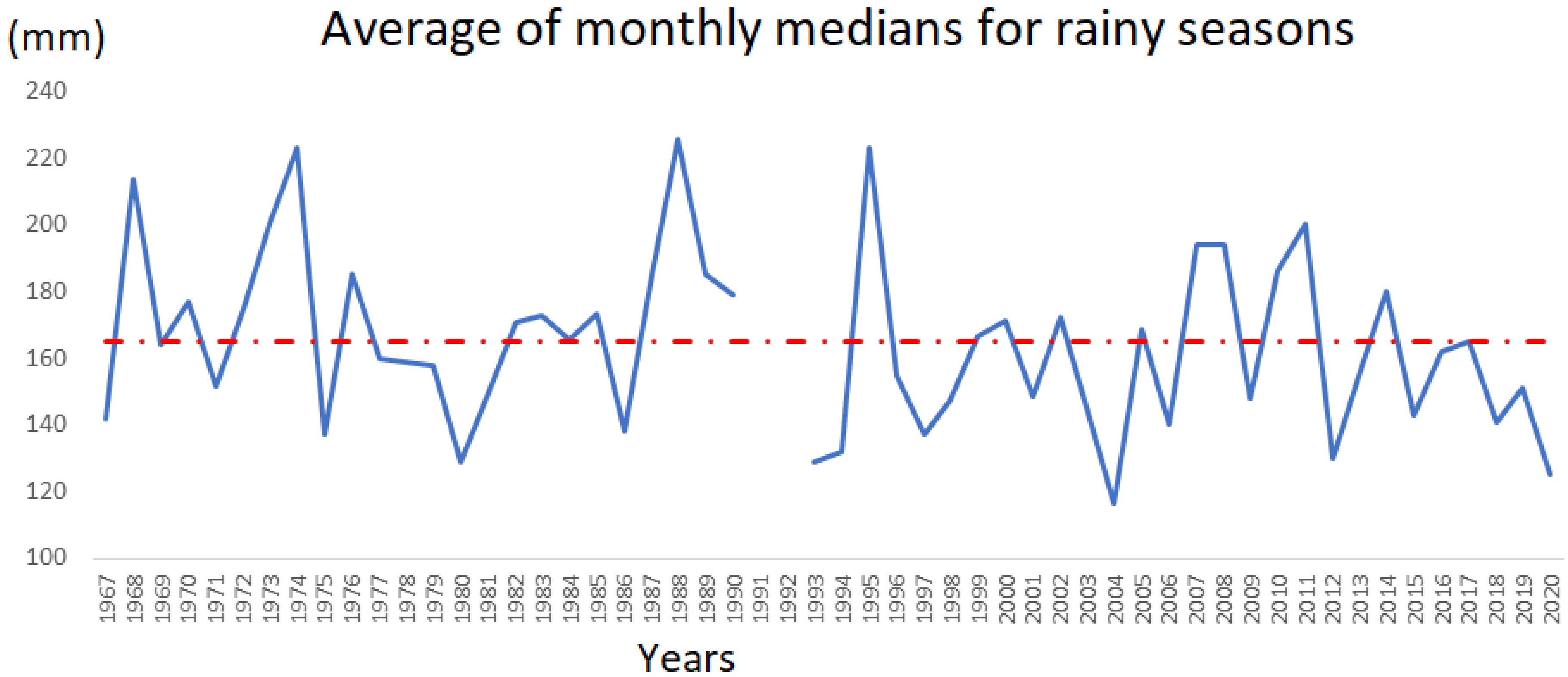
Fig_S1b. Hydrological conditions during the monitoring period of jaguars (2005 to 2016) and posterior years. Continuous lines correspond to yearly minimum river water depths (minimum quotas in meters from 2005 to 2020) at six Pantanal gauge stations in the Paraguay River. Dashed lines in the same colors correspond to the respective average of medians of minimums from six stations. Dashed-dotted line correspond to Annual Median Rain (reference 1967 to 2019). Histograms correspond to the MapBiomas yearly wetland estimated area (ha) in Pantanal areas of Mato Grosso (MT) and Mato Grosso do Sul (MS) from 2005 to 2019[29]. Dashed lines in the same colors correspond to the respective averages (1985 to 2019).



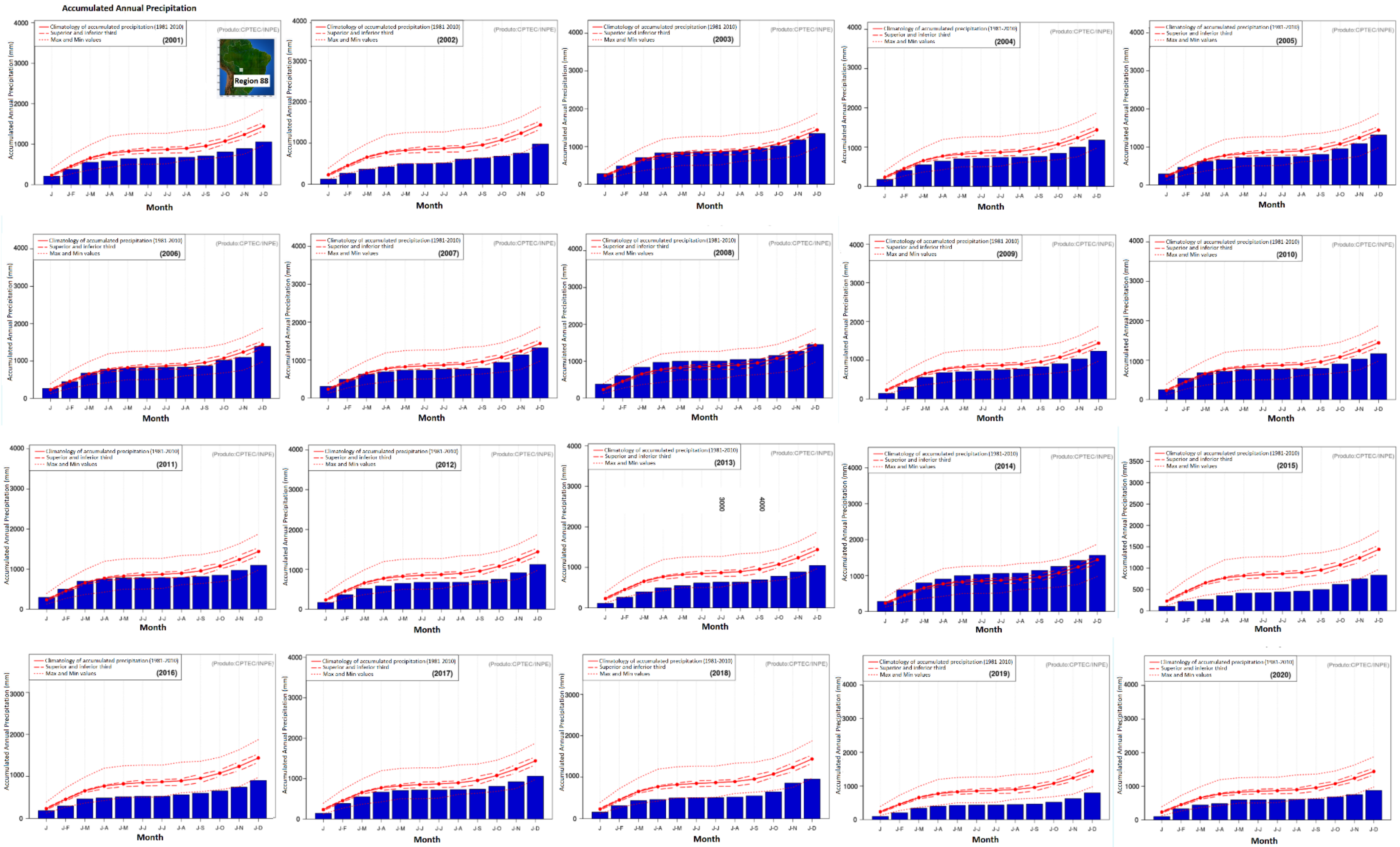
Fig_S2a. Quarterly precipitation in 2020 in comparison to the precipitation in the reference period (1981 – 2010)[24].



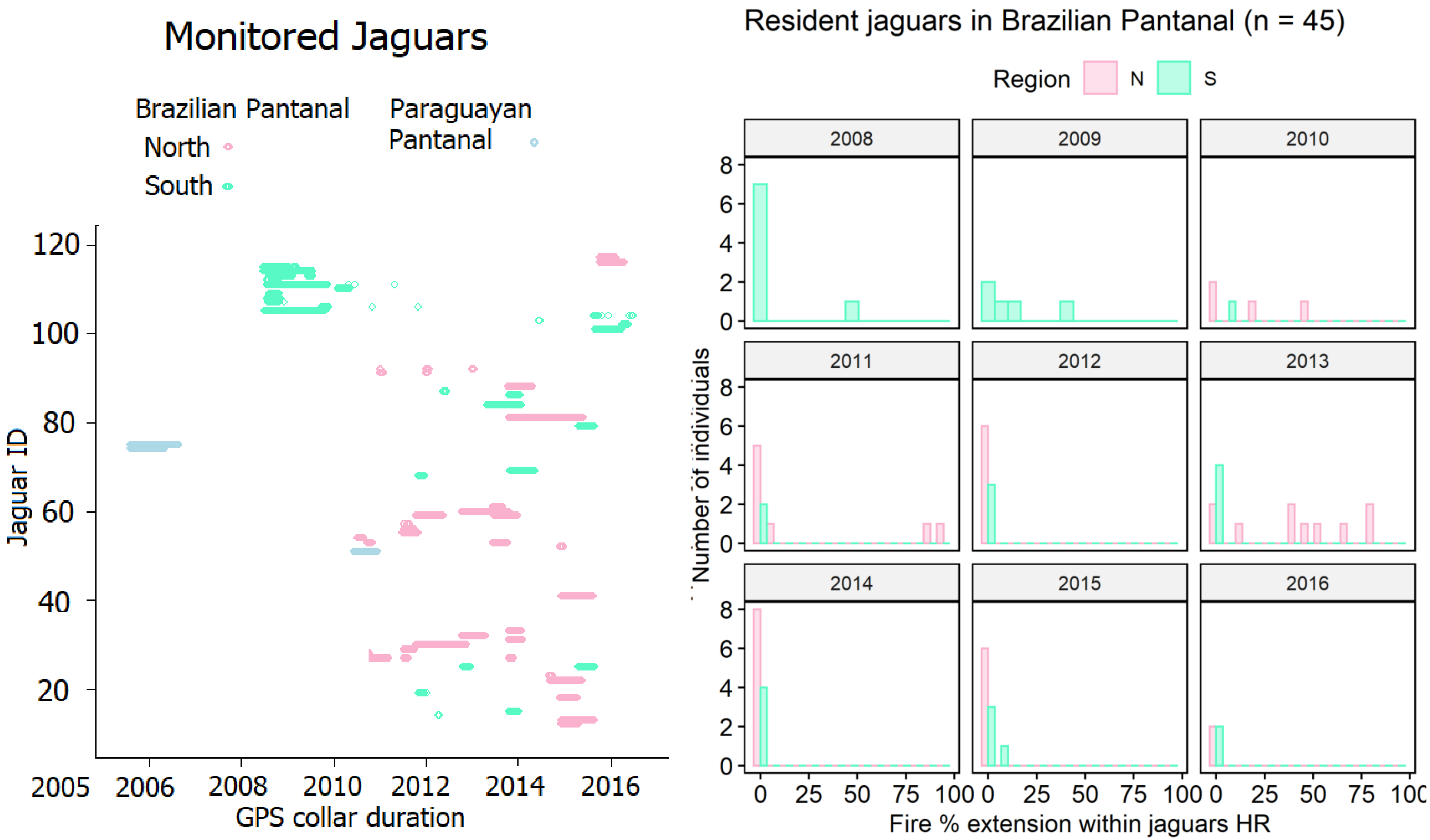
Fig_S2b. Monthly precipitation per year[25] with year 2020 in evidence. Data acquired for 2020 was limited until October.



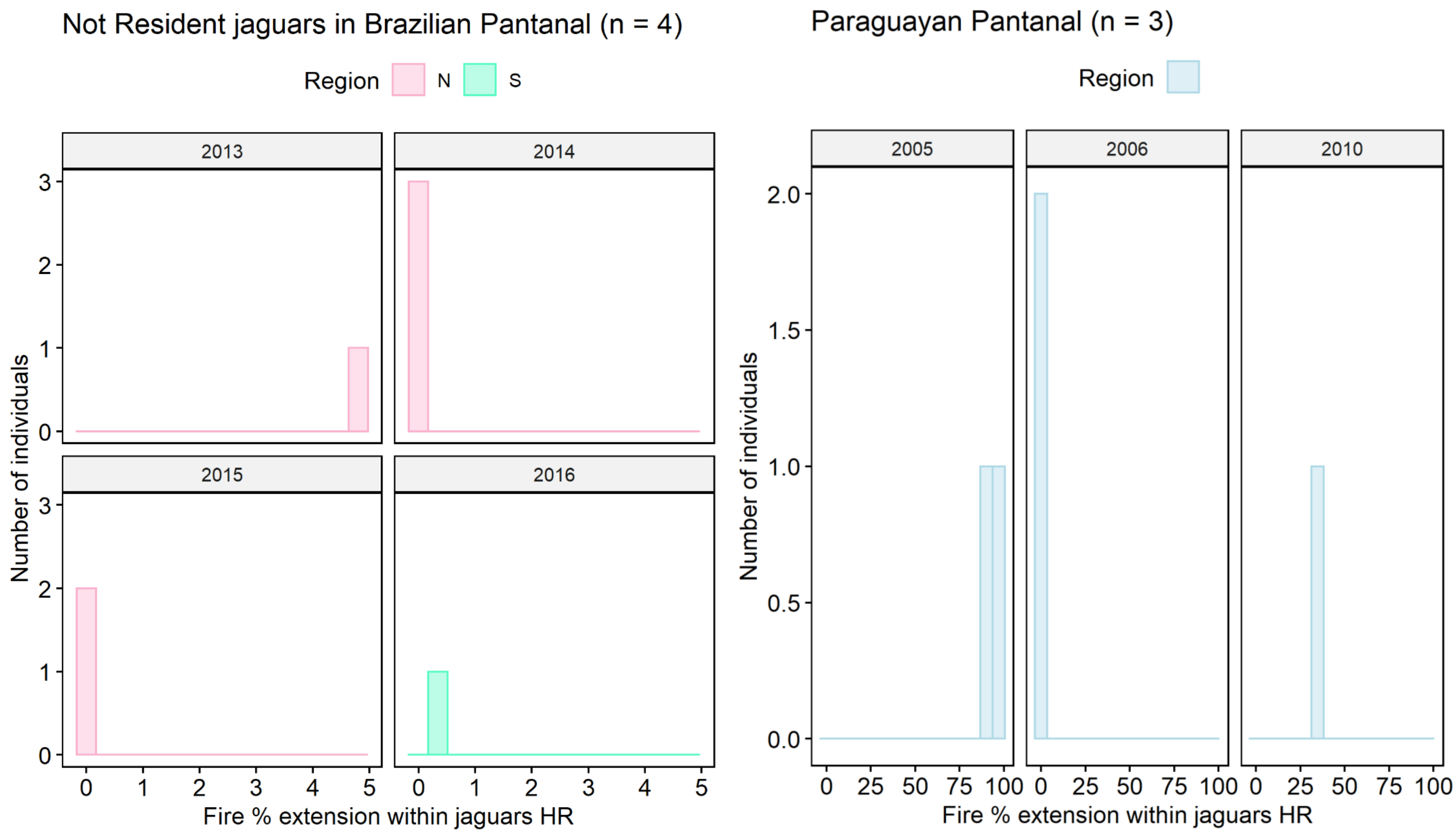
Fig_S2c. Average of monthly medians for rainy seasons (considering 4 stations: Cáceres, Corumbá, Cuiabá and Campo Grande) [25]. Note that 28 years had estimates below historical average. With five years (1980, 1993, 1994, 2004, 2012) having estimates more than 20% below historical average[25].Data acquired for 2020 limited until October.



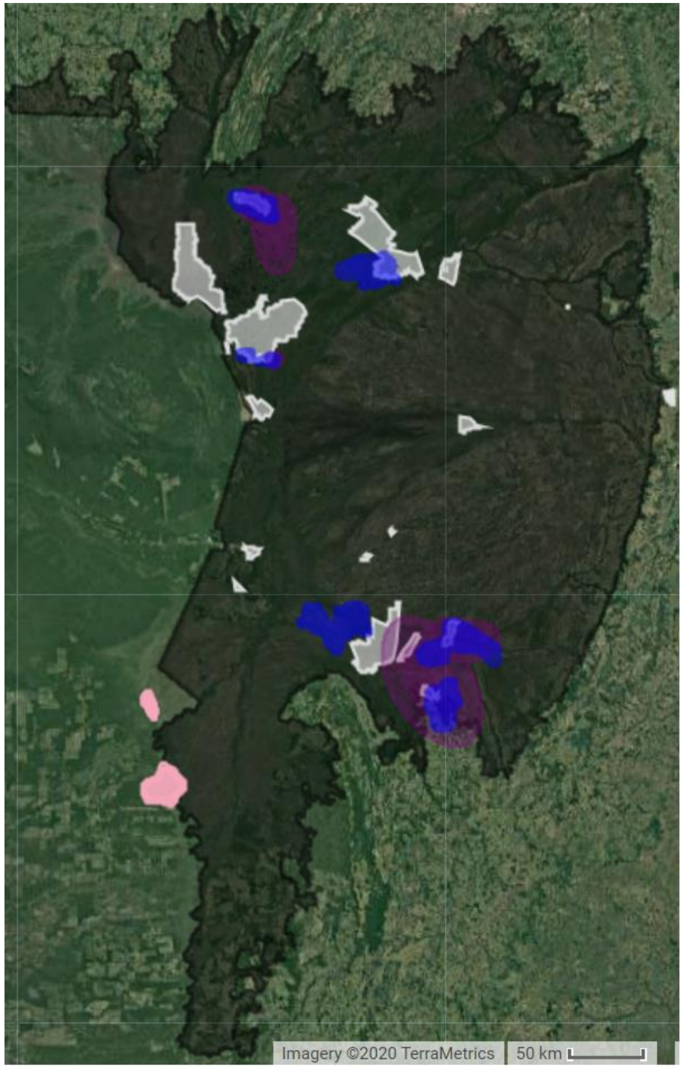
Fig_S2d. Accumulated precipitation from 2001 to 2020. Note that after 2014 accumulated precipitation values fall often below the minimums (reference period 1981 – 2010, translated and adapted from CPTEC/INPE)[24].



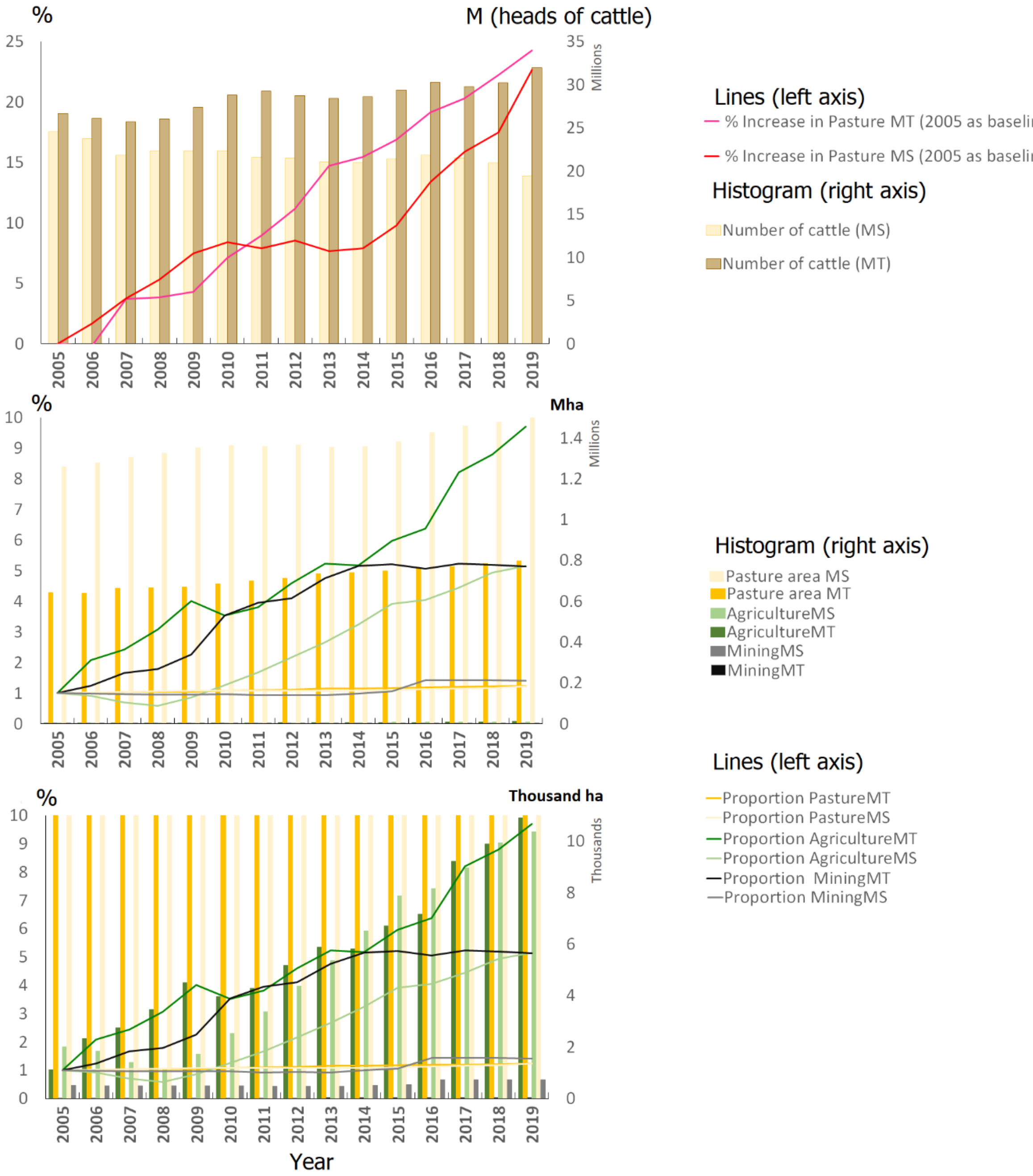
Fig_S3a. Left panel shows the GPS collars monitoring period of individual jaguars [48]. Right panel presents the reference study in which the percentual of fire impact on jaguar HR match each individual jaguar's monitoring period in Brazilian Pantanal.



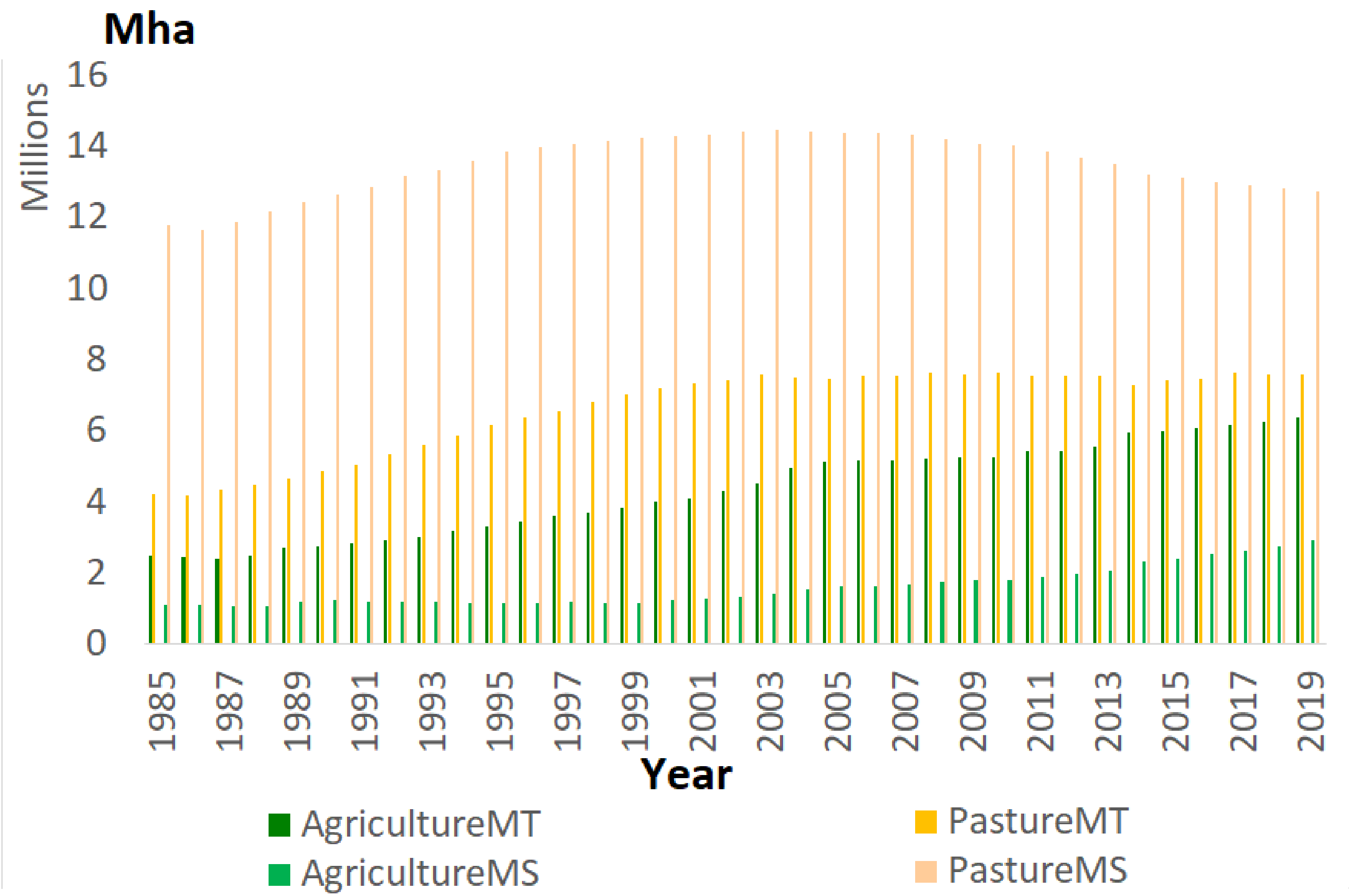
Fig_S3b. Reference study with percentual occurrence of fire matching individual jaguar areas during the monitoring period. Not resident jaguars in Brazil (left) and Residents from Paraguay (right). Note the low occurrence of fires within the areas used by Not Residents.



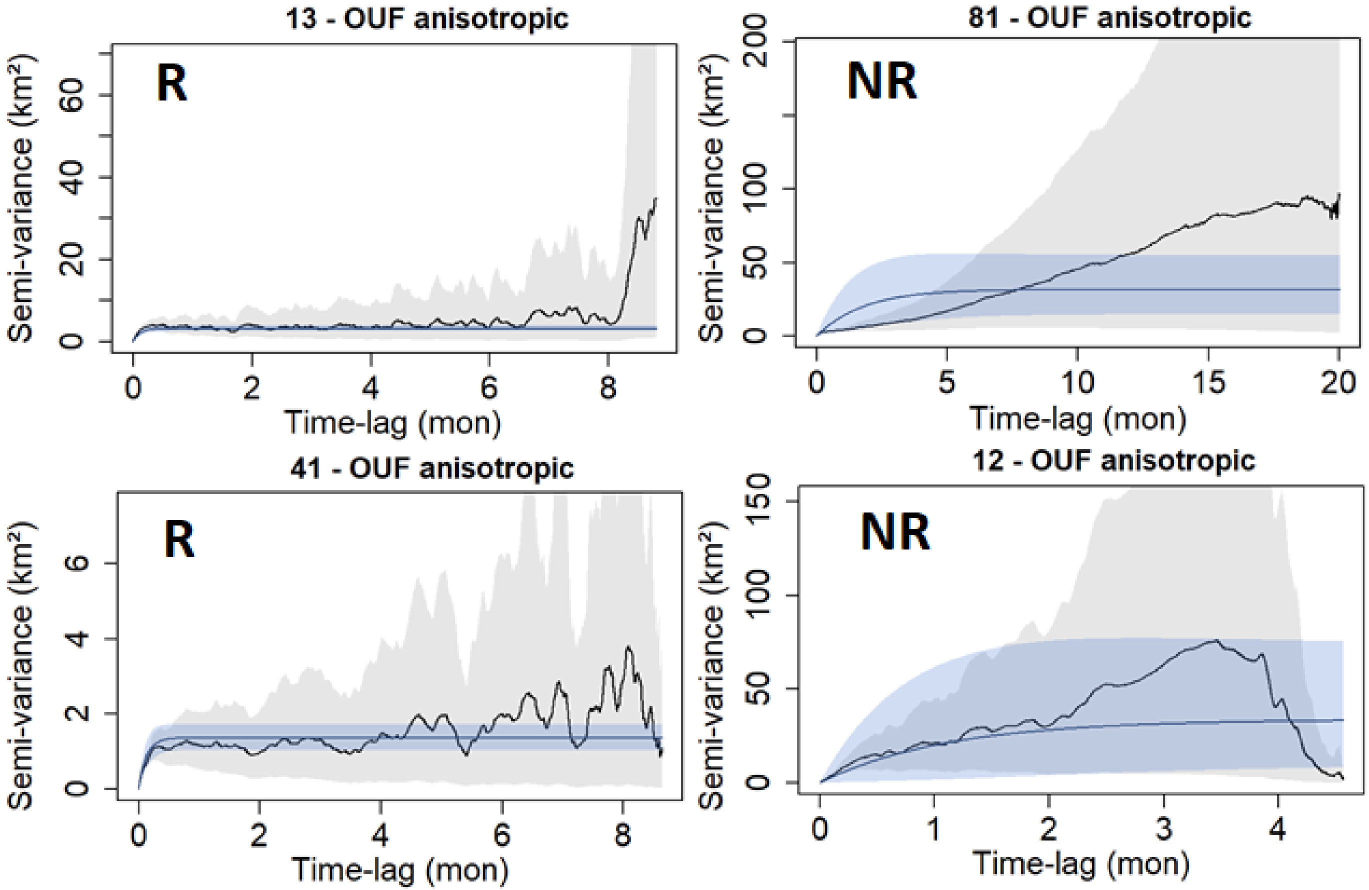
Fig_S4 Resident jaguars (blue), Not Residents (purple) and jaguars from Paraguayan Pantanal (salmon).



Fig_S5a Comparison of main anthropic activities in Pantanal (states of Mato Grosso MT and Mato Grosso do Sul). Cattle livestock is the most abundant economic activity and still increasing in both states MT and MS within Pantanal. Although the number of heads of cattle and pasture areas in Cerrado areas dropped (see Fig_S5b). Nonetheless, agriculture presented the highest percentual growth (MapBiomas data)[29].



Fig_S5b. Main anthropic activities in Cerrado (states of Mato Grosso MT and Mato Grosso do Sul, MapBiomas data)[29]. Cattle livestock is still the most abundant economic activity but area occupied by agriculture is increasing (particularly Soy bean)[29].



Fig_S6. Variogram of two resident jaguars (R) at the left, and two not-residents (NR) at right, from Brazilian Pantanal. The fitted best models are represented by the blue line accompanied of their respective 95% CI[99]. Not resident jaguars lack a clear asymptote despite the long monitoring time, what reflects also in a low effective number of range crossings. Numbers at the top are individual identifiers and OUF anisotropic correspond to the best fitted model (Ornstein-Uhlenbeck-F), denotating movement autocorrelation for position and speed for all R and NR jaguars shown above.