Elevated fires during COVID-19 lockdown and the vulnerability of protected areas

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Supplementary Information for

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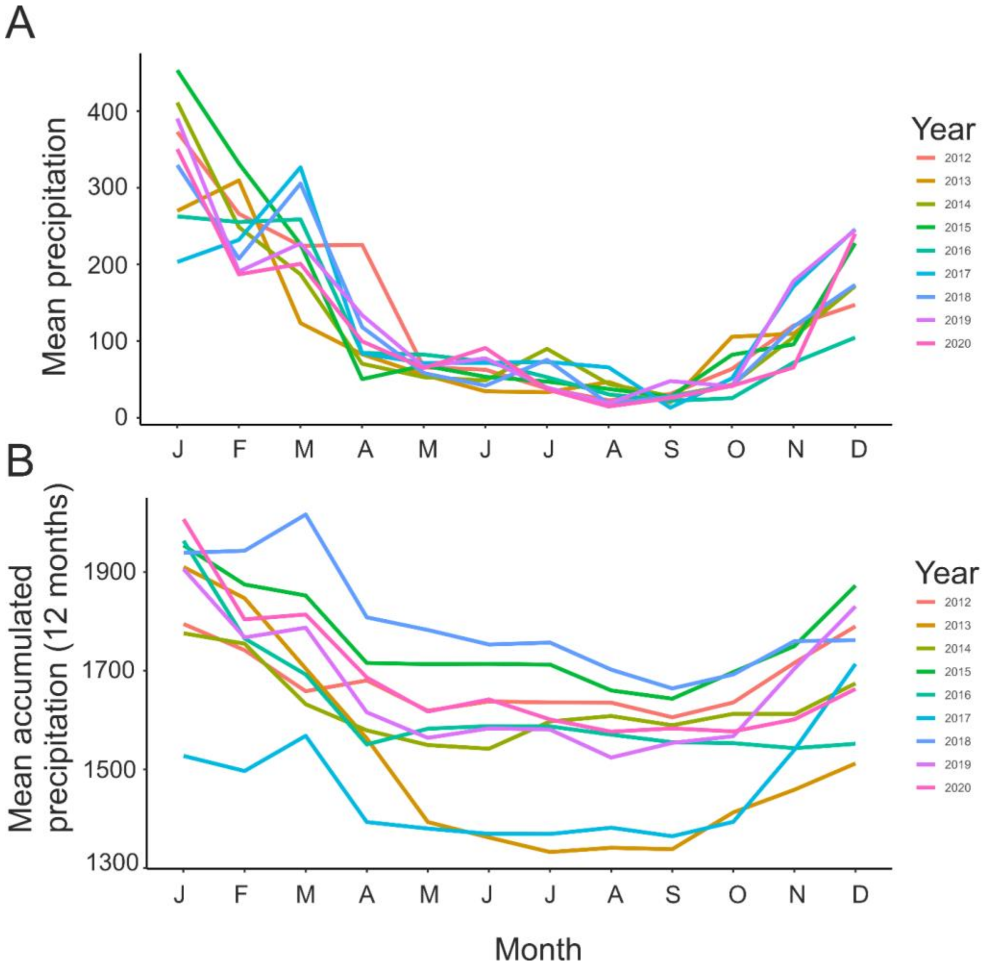

Figure S1. Yearly seasonal patterns in A) mean precipitation (mm) and B) mean accumulated precipitation (mm) over the 12 last months.

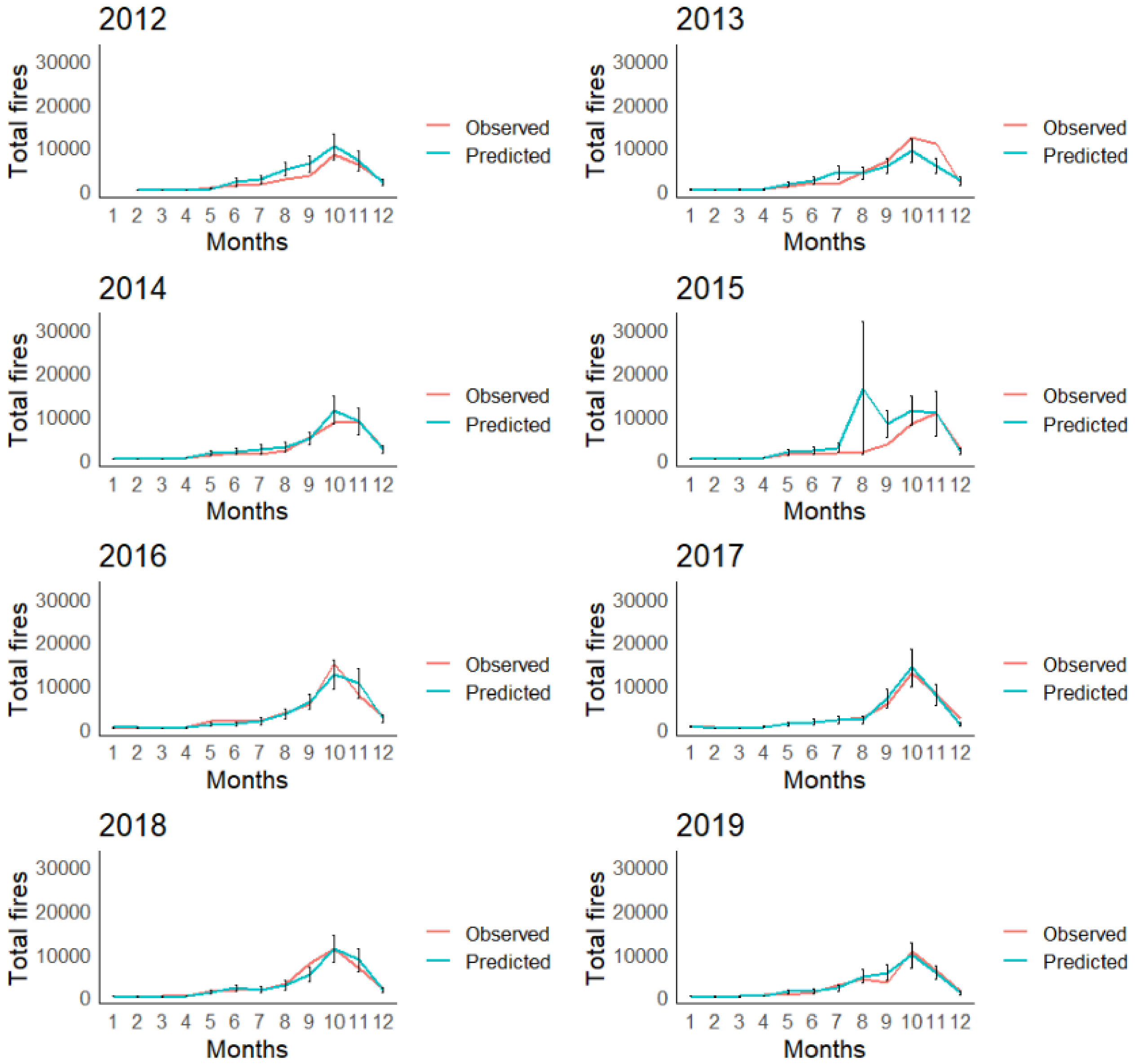

Figure S2. Observed versus predicted number of fires for all months in all years. Error bars show the 95% confidence intervals around the predictions and were generated by bootstrapping (predicted values resampled 10 000 times for each month of each year).

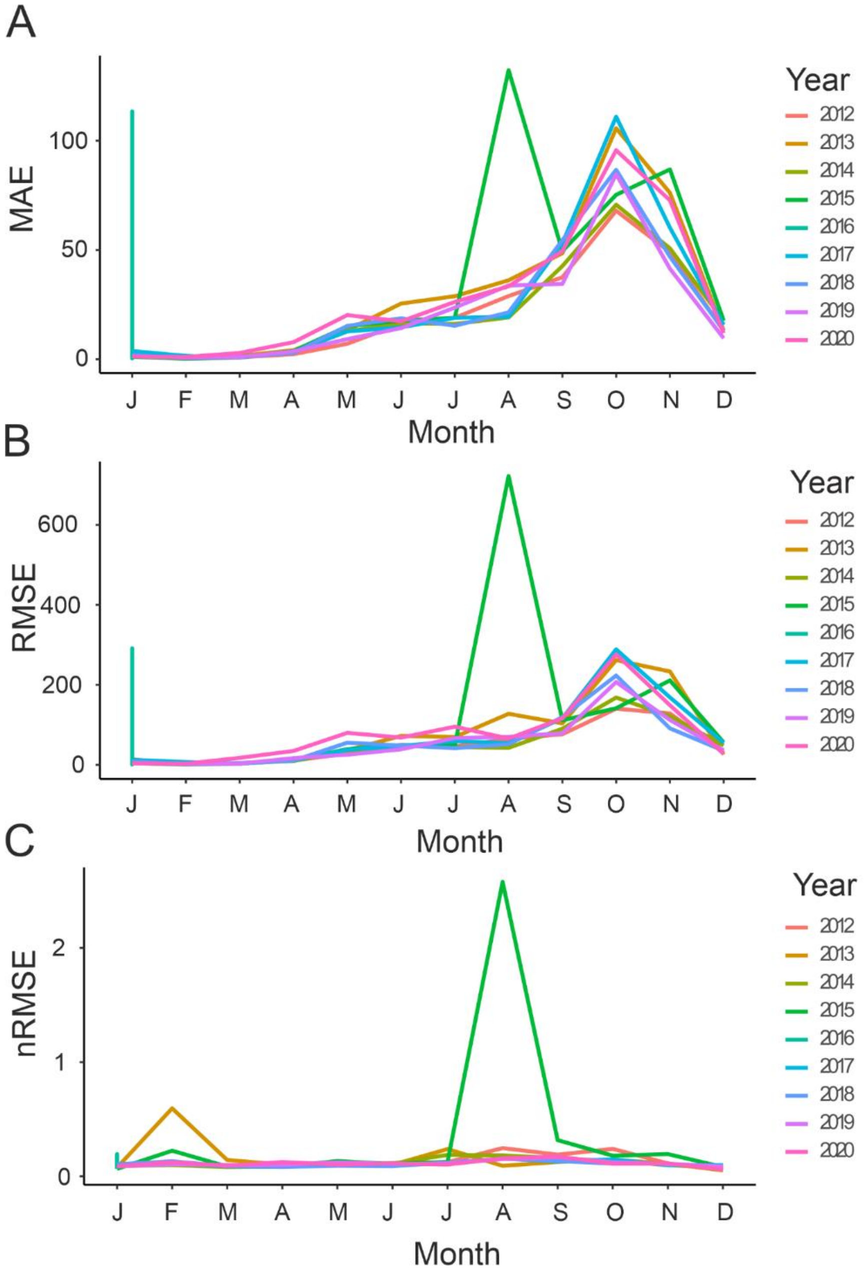

Figure S3. Forecast accuracy of our model for all months of each year as depicted by A) Mean Absolute Error (MAE), B) Root Mean Squared Error (RMSE), and C) Normalized Root Mean Squared Error (nRMSE). Note that MEA and RMSE are absolute measures, whereas nRMSE allows for comparison across periods of very different fire frequency as it avoids scale dependency. All are sensitive to outliers: three protected areas explain the extreme August 2015 values. See further investigation in SI below.

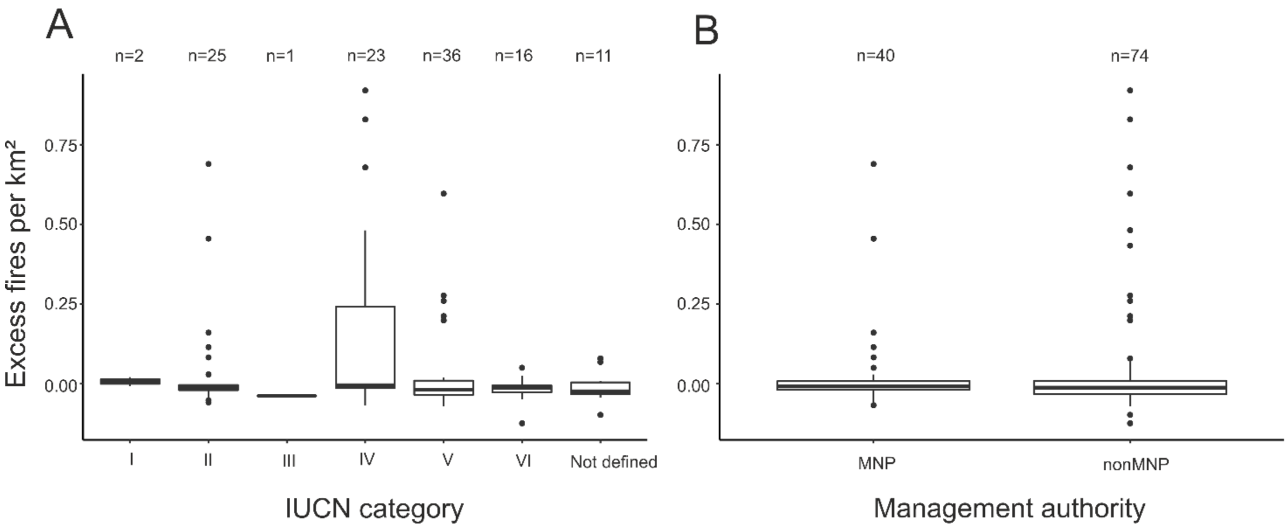

Figure S4. Boxplots of excess fires per km^2 (March-April 2020) for PAs in relation to their A) IUCN categories and B) management authority. The differences between categories are not significant as estimated by Kruskal–Wallis one-way analyses of variance (for IUCN category: chi-squared = 7.908, df = 6, p-value = 0.245; for management authority chi-squared = 1.260, df = 1, p-value = 0.262.

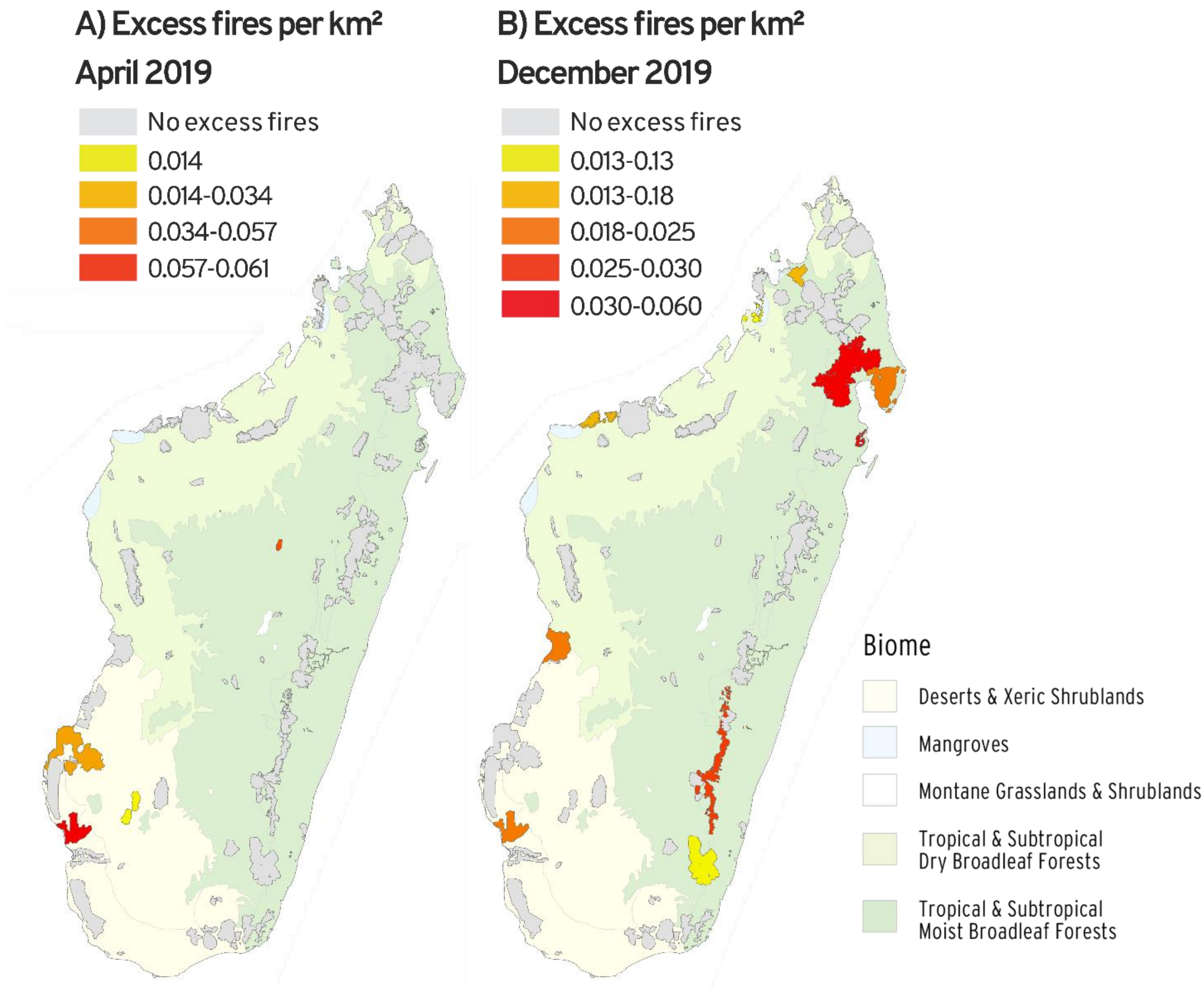

Figure S5. Geographical location of protected areas with excess fires in 2019 during the months with statistically more observed fires than predicted. A) April 2019 and B) December 2019.

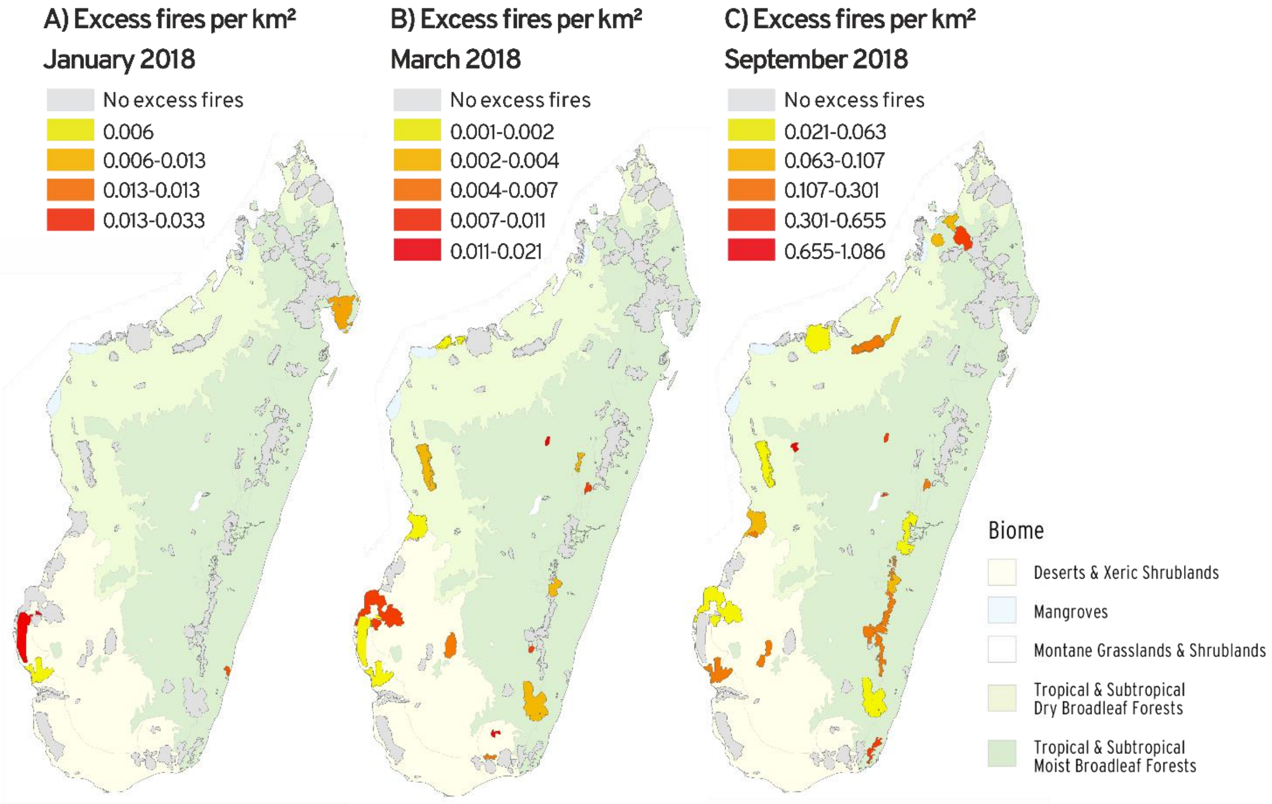

Figure S6. Geographical location of protected areas with excess fires in 2018 during the months with statistically more observed fires than predicted. A) January 2018, B) March 2018, C) September 2018.

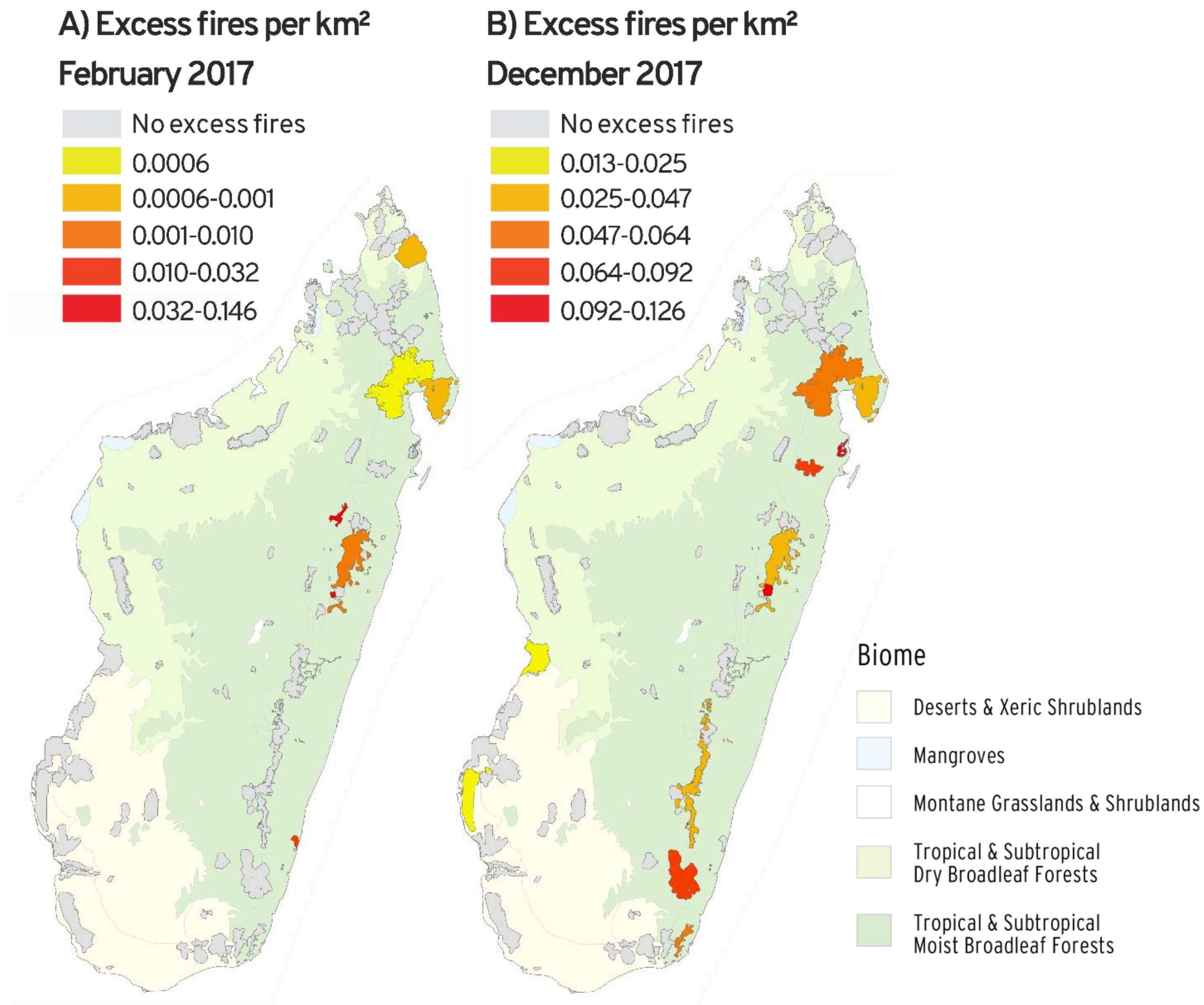

Figure S7. Geographical location of protected areas with excess fires in 2017 during the months with statistically more observed fires than predicted. A) February 2017 and B) December 2017.

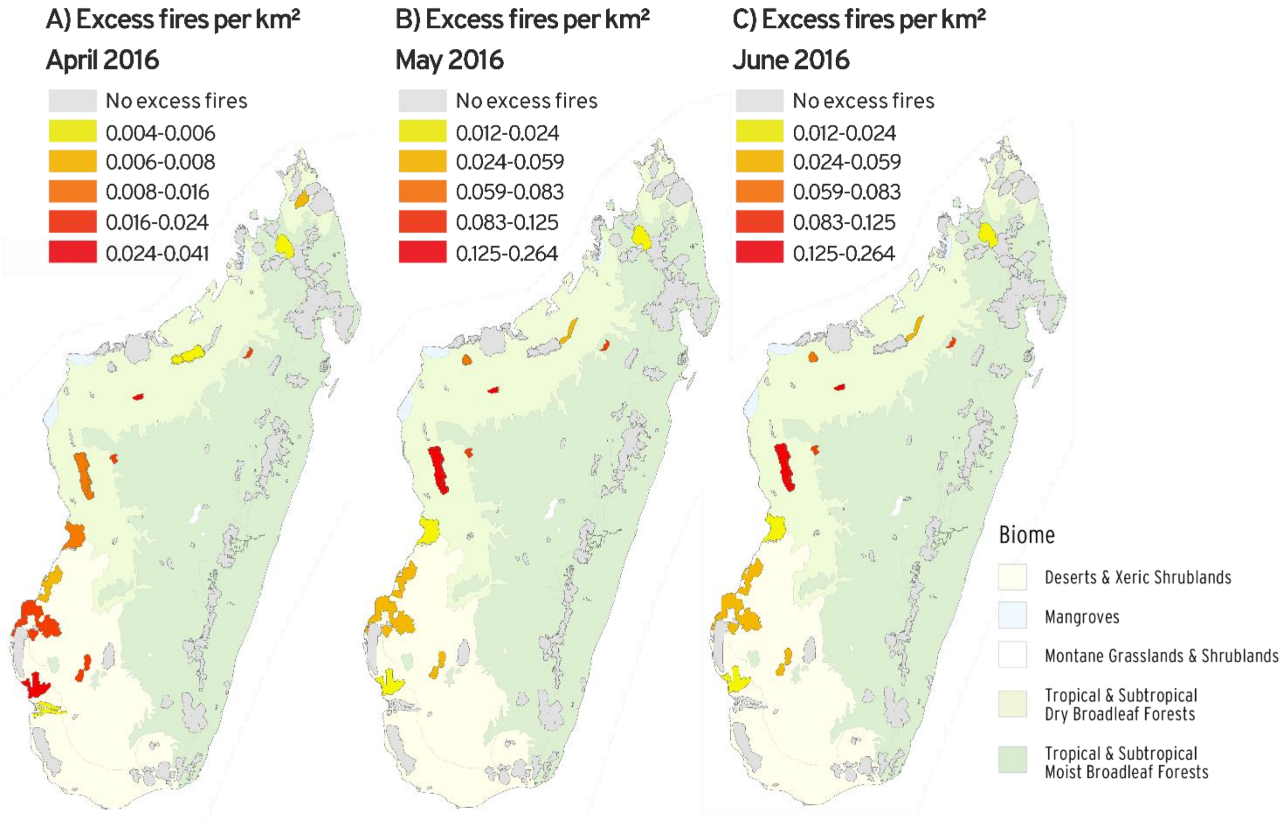

Figure S8. Geographical location of protected areas with excess fires in 2016 during the months with statistically more observed fires than predicted. A) April 2016, B) May 2016, C) June 2016.

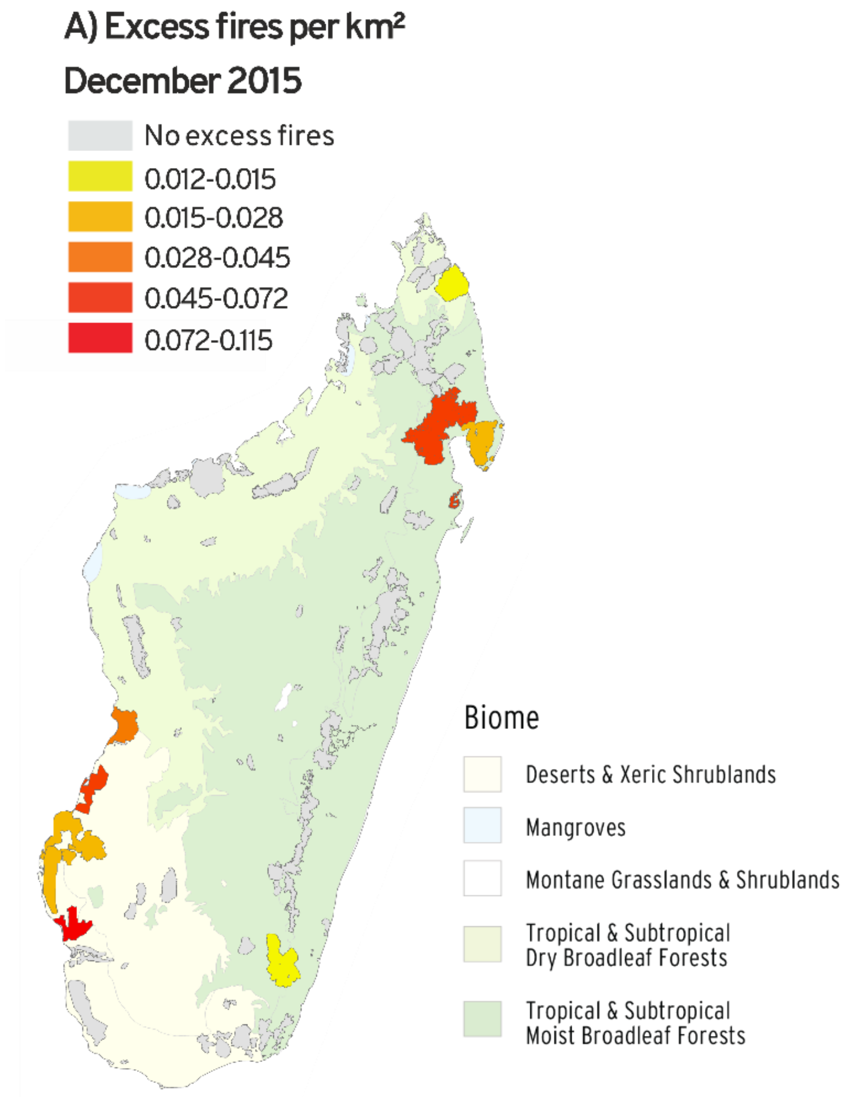

Figure S9. Geographical location of protected areas with excess fires in 2015 during the months with statistically more observed fires than predicted. A) December 2015.

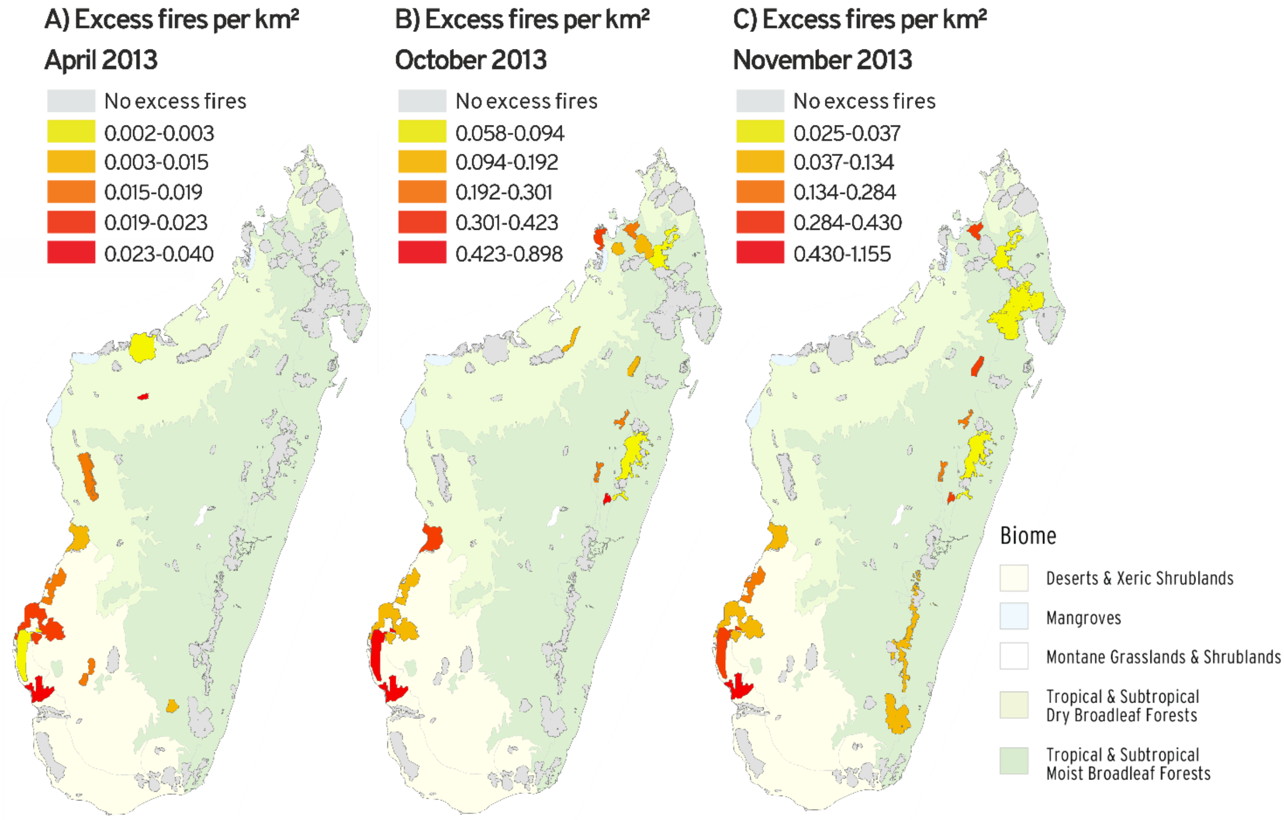

Figure S10. Geographical location of protected areas with excess fires in 2013 during the months with statistically more observed fires than predicted. A) April 2013, B) October 2013, C) November 2013.

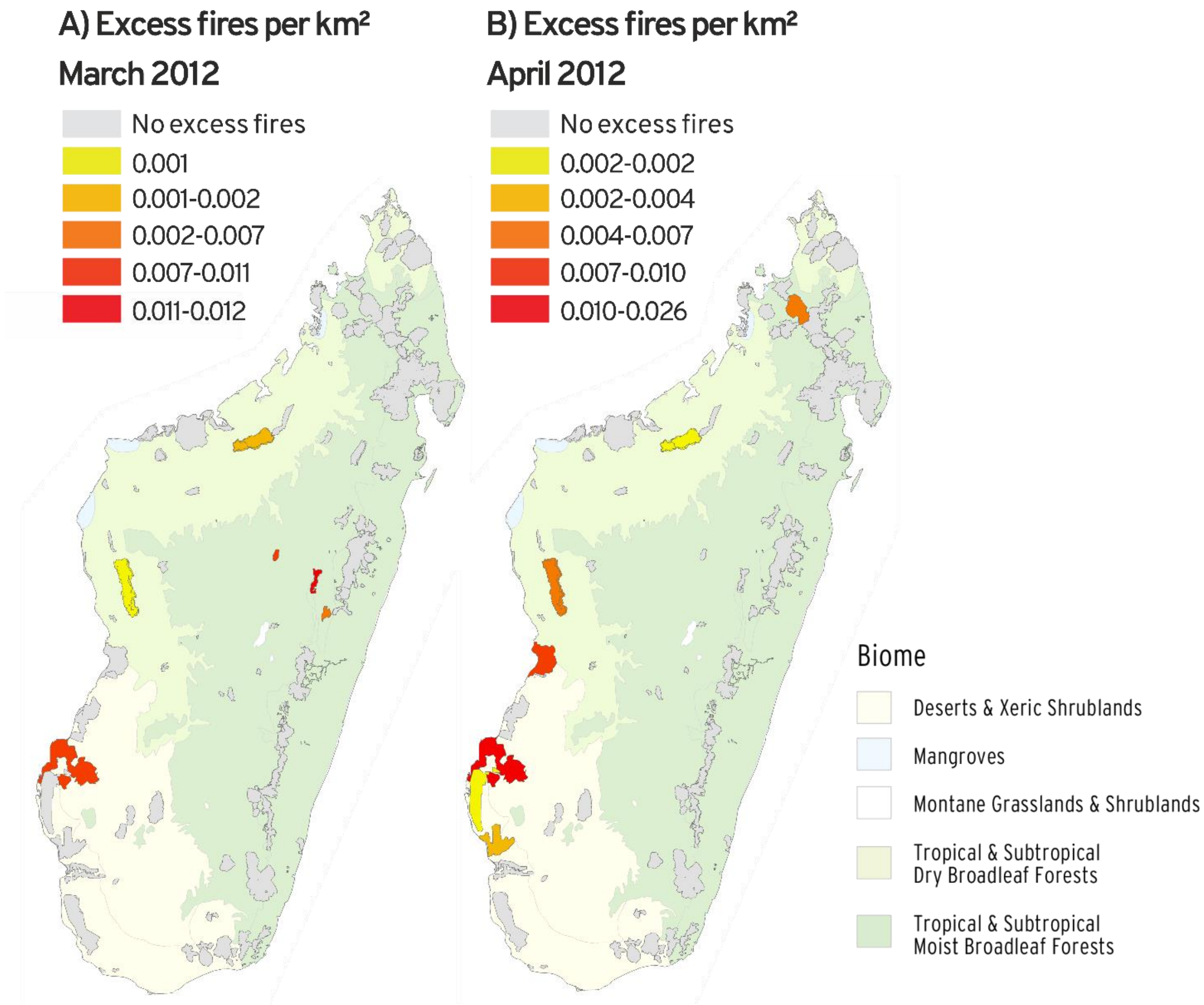

Figure S11. Geographical location of protected areas with excess fires in 2012 during the months with statistically more observed fires than predicted. A) March 2012 and B) April 2012.

Supplementary methods

Construction of timeline

The following news sites and webpages report the timing of important events and activities in relation to the Covid-19 pandemic in relation to conservation and were used for creating the timeline (Fig. 3).

Table S1. List of news sites and webpages sourced for information in relation to the timing of COVID-19 related actions.

URL address	Date accessed
https://www.who.int/emergencies/diseases/novel-coronavirus-2019/interactive-timeline#!	5.6.2021
https://www.nytimes.com/article/coronavirus-timeline.html	5.6.2021
http://sdg.iisd.org/events/2020-un-biodiversity-conference/	5.6.2021
https://www.voaafrique.com/a/coronavirus-%C3%A0-madagascar-porter-un-cache-bouche-ou-balayer-le-trottoir-/5394232.html	27.7.2021
https://news.mongabay.com/2020/09/madagascar-reopens-national-parks-shuttered-by-covid-19/	17.9.2020
https://madagascar-tourisme.com/fr/alertes-de-voyage-pour-madagascar/	27.7.2021

In addition to this, we also consulted conservation managers and government authorities in Madagascar in relation to the specifics of protected area management actions and how these changed during 2020. We acknowledge the following people:

Tiana Andriamanana, Executive Director, Fanamby

Solo Hervé, former Chef de volet Tsaratanana, Madagascar National Parks

Fenohery Rakotondrasoa, Landscape manager, Northern Highlands, WWF Madagascar

Seheno Ramanantsoa, Chef de service pour les Aires Protégées, Ministère de l'Environnement et du Développemenet Durable

Cynthia Raveloson, Chef de Service de la Direction Régionale de l'Environnement et du Développement Durable

Comparing Zip versus Zinb for our data

The count component of a zero-inflated model can be modeled by a Poisson or negative binomial distribution. If there is overdispersion not caused by the zeros, then ZINB is usually better (Zuur et al. 2009). We compared the use of ZIP and ZINB for the months of January, April, July, and October 2020 to determine which model structure is better for our data. For January, the ZIP regression yielded a log-likelihood of -1739.2; while the ZINB yielded a log-likelihood of -814.0. The ZIP and ZINB models are nested so they can be compared by using the likelihood test for overdispersion (Zuur et al. 2009), which yields a statistic of 1850.5, $p < 2.2e-16$, which provide evidence for preferring the ZINB over the ZIP. For April, the ZIP regression yielded a log-likelihood of -2221.1; while the ZINB yielded a log-likelihood of -1131.3. The likelihood test for overdispersion yields a statistic of 2179.6 $p < 2.2e-16$, which provide further evidence for preferring the ZINB over the ZIP also during the spring. For July, the ZIP regression yielded a log-likelihood of -9846.1; while the ZINB yielded a log-likelihood of -2167.0. The likelihood test for overdispersion yields a statistic of 15358, $p < 2.2e-16$, which provide further evidence for preferring the ZINB over the ZIP also during the summer season. For October, the ZIP regression yielded a log-likelihood of -54903; while the ZINB yielded a log-likelihood of -3809. The likelihood test for overdispersion yields a statistic of 102188, $p < 2.2e-16$, which provide further evidence for preferring the ZINB over the ZIP also during the autumn fire season.

Inspecting the deviation in model accuracy for August 2015

From both figures S2 and S3 it is clear that our model performed poorly for August 2015. We inspected the underlying reasons for this and found that the deviation is caused primarily by three protected areas (Menabe Antimena, Kirindy Mite, and Complexe Zones Humides Mangoky Ihotry) that had higher accumulated rainfall during the previous12 months than during other years (Fig. S12). As accumulated rainfall in August tends to cause more burning (there is more biomass that can burn) this led to predictions of exceptionally high fire predictions, which did not materialize.

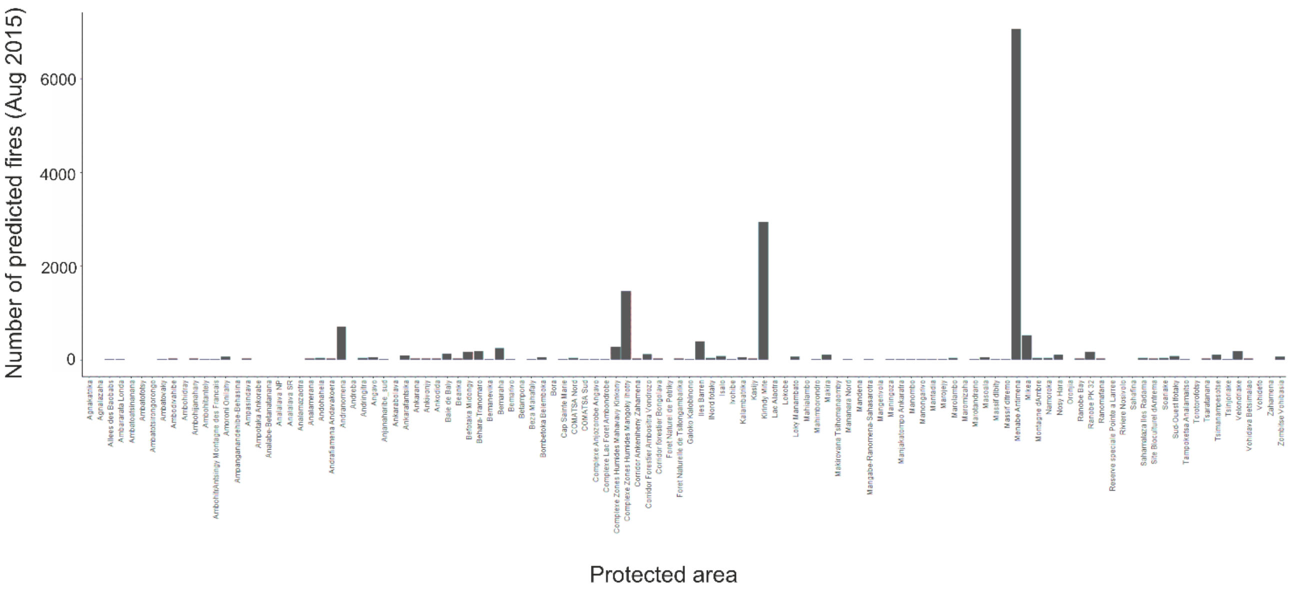

Figure S12. Predicted fires per protected area for August 2015.

<u>References</u>

Zuur, A.F., Ieno, E.N., Walker, N.J., Saveliev, A.A. & Smith, G.M. (2009). Zero-truncated and zero-inflated models for count data. In: *Mixed Effects Models and Extensions in Ecology with R*. Springer New York, pp. 261–293.

Supplementary tables

The tables containing the model summaries and parameter estimates for all months, all years, are available as a separate excel file. Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' '.

Table S2. Name, area, year of establishment, IUCN management category, and biome of the protected areas included in the study

Name of protected area	Area (km2)	Year created	IUCN category	Biome
Agnakatrika	7.88710486	2015	VI	Moist Broadleaf Forests
Agnalazaha	27.45313	2015	VI	Moist Broadleaf Forests
Allees des Baobabs	3.20521	2015	III	Deserts_Xeric Shrublands
Ambararata Londa	102.83706	2015	Not defined	Dry Broadleaf Forests
Ambatoatsinanana	7.3119	2015	V	Moist Broadleaf Forests
Ambatofotsy	15.93638	2015	V	Moist Broadleaf Forests
Ambatotsirongorongo	10.30048	2015	IV	Moist Broadleaf Forests
Ambatovaky	929.80291	1958	IV	Moist Broadleaf Forests
Ambodivahibe	465.61725	2015	V	Dry Broadleaf Forests
Ambohidray	12.41048	2015	Not defined	Moist Broadleaf Forests
Ambohijanahary	243.02027	1958	IV	Moist Broadleaf Forests
Ambohitantely	171.49386	1982	IV	Moist Broadleaf Forests
AmbohitrAntsingy Montagne des Francais	61.06793	2015	V	Dry Broadleaf Forests
Amoroni Onilahy	1020.71884	2015	V	Deserts_Xeric Shrublands
Ampanganandehibe-Behasina	5.79726	2015	V	Moist Broadleaf Forests
Ampasindava	915.34324	2015	V	Dry Broadleaf Forests
Ampotaka Ankorabe	0.972	2015	V	Moist Broadleaf Forests
Analabe-Betanatanana	3.58384	2015	VI	Moist Broadleaf Forests
Analalava NP	3.80393	2015	VI	Dry Broadleaf Forests
Analalava SR	2.24853	2015	IV	Moist Broadleaf Forests
Analamazaotra	26.53355	1970	II	Moist Broadleaf Forests
Analamerana	750.87743	1956	IV	Dry Broadleaf Forests
Andohahela	872.0592	1939	II	Moist Broadleaf Forests
Andrafiamena Andavakoera	733.19412	2015	V	Dry Broadleaf Forests

Andranomena	207.29321	1958	IV	Deserts_Xeric Shrublands
Andreba	0.39308	2015	V	Moist Broadleaf Forests
Andringitra	538.17053	1937	II	Moist Broadleaf Forests
Angavo	427.59941	2015	Not defined	Deserts_Xeric Shrublands
Anjanaharibe_sud	374.81984	1958	IV	Moist Broadleaf Forests
Ankarabolava	7.72423195	2015	VI	Moist Broadleaf Forests
Ankarafantsika	1695.32808	1927	II	Dry Broadleaf Forests
Ankarana	484.81103	1956	IV	Dry Broadleaf Forests
Ankivonjy	1394.3776	2015	V	Moist Broadleaf Forests
Ankodida	106.28513	2015	V	Deserts_Xeric Shrublands
Baie de Baly	1254.05374	1997	II	Dry Broadleaf Forests
Beanka	171.84626	2015	V	Dry Broadleaf Forests
Befotaka Midongy	3111.66707	1997	II	Moist Broadleaf Forests
Behara-Tranomaro	965.87774	2015	Not defined	Deserts_Xeric Shrublands
Bemanevika	356.06083	2015	V	Moist Broadleaf Forests
Bemaraha	2316.31083	1927	II	Dry Broadleaf Forests
Bemarivo	120.46313	1956	IV	Dry Broadleaf Forests
Betampona	41.47355	1927	I	Moist Broadleaf Forests
Beza Mahafaly	77.67025	1986	IV	Deserts_Xeric Shrublands
Bombetoka Belemboka	719.43496	2015	Not defined	Dry Broadleaf Forests
Bora	40.52102	1956	IV	Dry Broadleaf Forests
COMATSA Nord	2378.77069	2015	VI	Moist Broadleaf Forests
COMATSA Sud	802.03973	2015	V	Moist Broadleaf Forests
Cap Sainte Marie	62.97775	1962	IV	Deserts_Xeric Shrublands
Complexe Anjozorobe Angavo	411.02227	2015	V	Moist Broadleaf Forests
Complexe Lac Foret Ambondrobe	70.2752	2015	V	Dry Broadleaf Forests
Complexe Zones Humides Mahavavy Kinkony	3509.27558	2015	V	Dry Broadleaf Forests
Complexe Zones Humides Mangoky Ihotry	4265.75619	2015	V	Deserts_Xeric Shrublands
Corridor Ankeniheny Zahamena	3691.89154	2015	VI	Moist Broadleaf Forests

Corridor Forestier Ambositra Vondrozo	3131.03504	2015	V	Moist Broadleaf Forests
Corridor forestier Bongolava	605.89816	2015	V	Dry Broadleaf Forests
Foret Naturel de Petriky	3.01869	2015	V	Moist Broadleaf Forests
Foret Naturelle de Tsitongambarika	585.97801	2015	VI	Moist Broadleaf Forests
Galoko Kalobinono	750.0942	2015	V	Moist Broadleaf Forests
INord fotaky	224.26534	2015	V	Deserts_Xeric Shrublands
Iles Barren	4632	2014	Not defined	Dry Broadleaf Forests
Isalo	1133.74187	1962	II	Deserts_Xeric Shrublands
Ivohibe	148.14951	1964	IV	Moist Broadleaf Forests
Kalambatrika	524.25736	1959	IV	Moist Broadleaf Forests
Kasijy	229.56386	1956	IV	Dry Broadleaf Forests
Kirindy Mite	2374.03281	1997	II	Deserts_Xeric Shrublands
Lac Alaotra	424.79662	2015	V	Moist Broadleaf Forests
Lokobe	15.10145	1927	II	Moist Broadleaf Forests
Loky Manambato	2484.09453	2015	V	Dry Broadleaf Forests
Mahialambo	3.04007	2015	V	Moist Broadleaf Forests
Mahimborondro	751.62175	2015	VI	Moist Broadleaf Forests
Makira	7224.90399	2012	II	Moist Broadleaf Forests
Makirovana Tsihomanaomby	33.866	2015	VI	Moist Broadleaf Forests
Mananara Nord	312.76494	1989	II	Moist Broadleaf Forests
Mandena	4.37112	2015	V	Moist Broadleaf Forests
Mangabe-Ranomena-Sahasarotra	271.31518	2015	VI	Moist Broadleaf Forests
Mangerivola	270.47121	1958	IV	Moist Broadleaf Forests
Maningoza	59.72619	1956	NA	Dry Broadleaf Forests
Manjakatompo Ankaratra	81.3097	2015	VI	Moist Broadleaf Forests
Manombo	205.554	1962	IV	Moist Broadleaf Forests
Manongarivo	643.55533	1956	IV	Moist Broadleaf Forests

Mantadia	330.07213	1989	II	Moist Broadleaf Forests
Marojejy	752.67436	1952	II	Moist Broadleaf Forests
Marolambo	1942.9054	2015	II	Moist Broadleaf Forests
Maromizaha	19.39869	2015	VI	Moist Broadleaf Forests
Marotandrano	671.19132	1956	IV	Moist Broadleaf Forests
Masoala	3100.94724	1927	II	Moist Broadleaf Forests
Massif dIbity	61.36602	2015	V	Moist Broadleaf Forests
Massif dItremo	246.96443	2015	V	Moist Broadleaf Forests
Menabe Antimena	2094.60834	2015	V	Deserts_Xeric Shrublands
Mikea	2367.36907	2011	II	Deserts_Xeric Shrublands
Montagne dAmbre	586.69745	1958	II	Moist Broadleaf Forests
Namoroka	379.46173	1927	II	Dry Broadleaf Forests
Nosy Hara	1833.49943	2011	II	Dry Broadleaf Forests
Oronjia	16.59451	2015	V	Dry Broadleaf Forests
Ranobe Bay	424.04024	2015	Not defined	Deserts_Xeric Shrublands
Ranobe PK 32	1685.00237	2015	Not defined	Deserts_Xeric Shrublands
Ranomafana	728.26567	1991	II	Moist Broadleaf Forests
Reserve speciale Pointe a Larree	7.7065	2015	IV	Moist Broadleaf Forests
Riviere Nosivolo	67.81198	2015	V	Moist Broadleaf Forests
Sahafina	24.06855	2015	V	Moist Broadleaf Forests
Sahamalaza Iles Radama	1120.16945	2007	II	Dry Broadleaf Forests
Site Bioculturel dAntrema	204.342588 1	2015	VI	Dry Broadleaf Forests
Soariake	382.91263	2015	VI	Deserts_Xeric Shrublands
Sud-Ouest Ifotaky	570.6205	2015	Not defined	Deserts_Xeric Shrublands
Tampoketsa Analamaitso	225.62187	1958	IV	Moist Broadleaf Forests
Torotorofotsy	97.644	2015	Not defined	Moist Broadleaf Forests
Tsaratanana	1490.64401	1927	I	Moist Broadleaf Forests

Tsimanampesotse	2629.58652	1927	II	Deserts_Xeric Shrublands
Tsinjoriake	147.95268	2015	V	Deserts_Xeric Shrublands
Velondriake	813.39356	2015	V	Deserts_Xeric Shrublands
Vohidava Betsimalao	181.07365	2015	VI	Deserts_Xeric Shrublands
Vohidefo	50.56182	2015	Not defined	Deserts_Xeric Shrublands
Zahamena	692.49351	1927	II	Moist Broadleaf Forests
Zombitse Vohibasia	806.72113	1997	II	Deserts_Xeric Shrublands