# Supplementary Information for

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

**Author list:** Johanna Eklund[1*], Julia P G Jones[2], Matti Räsänen[3], Jonas Geldmann[4], Ari-Pekka Jokinen[1], Adam Pellegrini[5], Domoina Rakotobe[6], O. Sarobidy Rakotonarivo[7], Tuuli Toivonen[1], and Andrew Balmford[8]

**Affiliations:**

1. Digital Geography Lab, Department of Geosciences and Geography, Faculty of Sciences, University of Helsinki, Finland
2. School of Natural Sciences, College of Environmental Sciences and Engineering, Bangor University, UK
3. Institute for Atmospheric and Earth System Research, University of Helsinki, Finland
4. Center for Macroecology, Evolution and Climate, Globe Institute, University of Copenhagen, Denmark
5. Department of Plant Sciences, University of Cambridge, Cambridge, UK
6. Department of Geography, Universite d'Antananarivo, Antananarivo, Madagascar – Environmental Sciences Department, Ohio University, USA.
7. École Supérieure des Sciences Agronomiques, Université d'Antananarivo, Antananarivo, Madagascar
8. Conservation Science Group, Department of Zoology, University of Cambridge, UK

*corresponding author: johanna.f.eklund@helsinki.fi

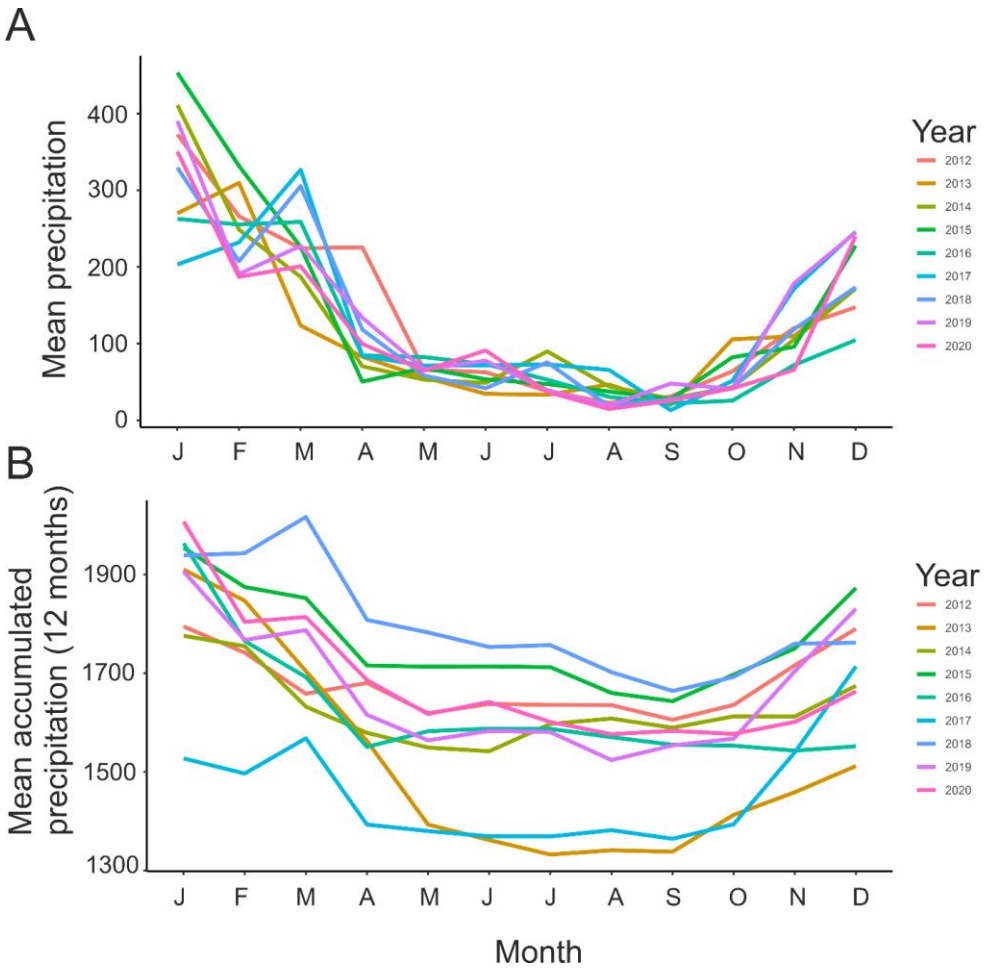



**Figure S1.** Yearly seasonal patterns in A) mean precipitation (mm) and B) mean accumulated precipitation (mm) over the 12 last months.

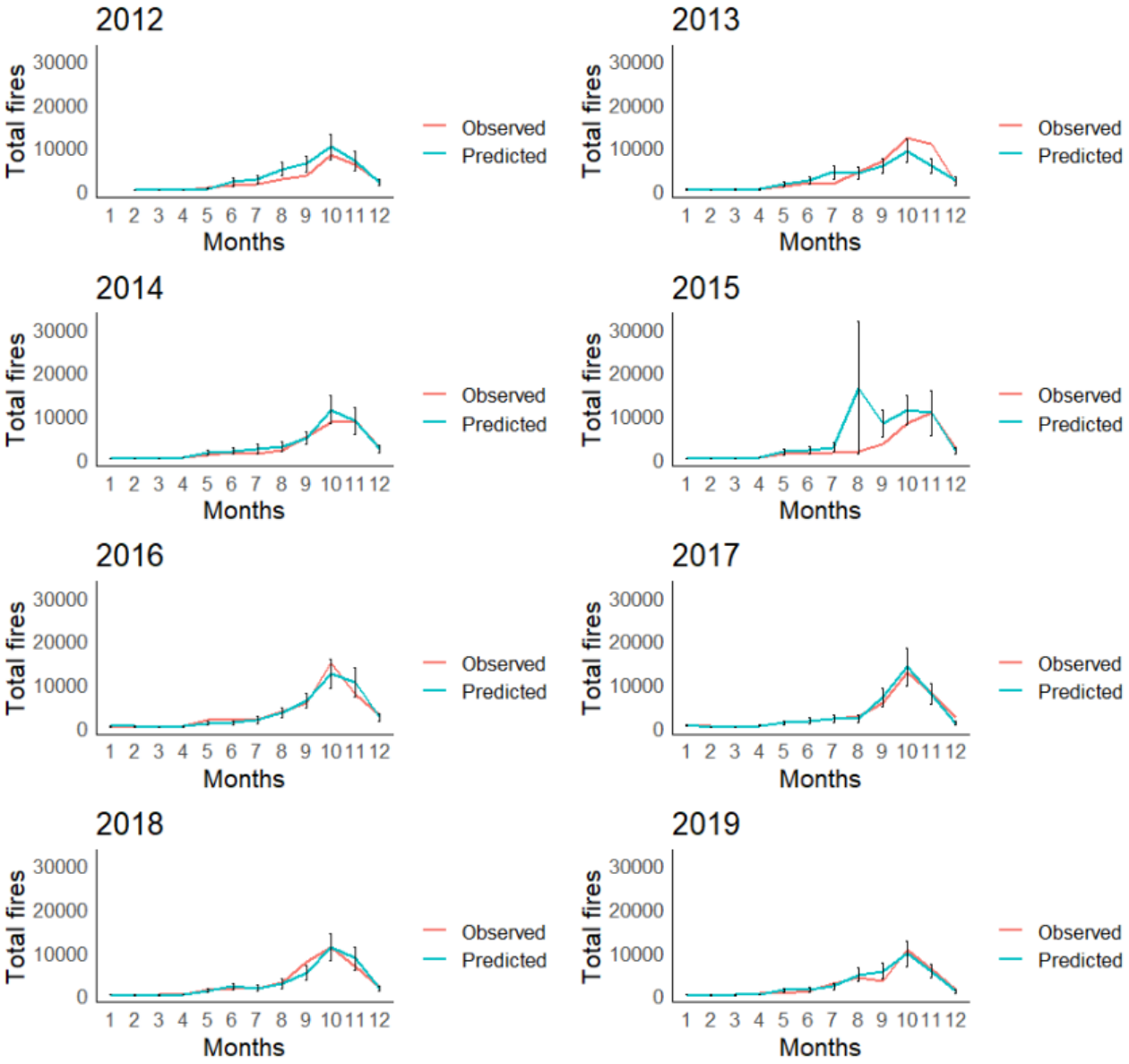



**Figure S2**. Observed versus predicted number of fires for all months in all years. Error bars show the 95% confidence intervals around the predictions and were generated by bootstrapping (predicted values resampled 10 000 times for each month of each year).

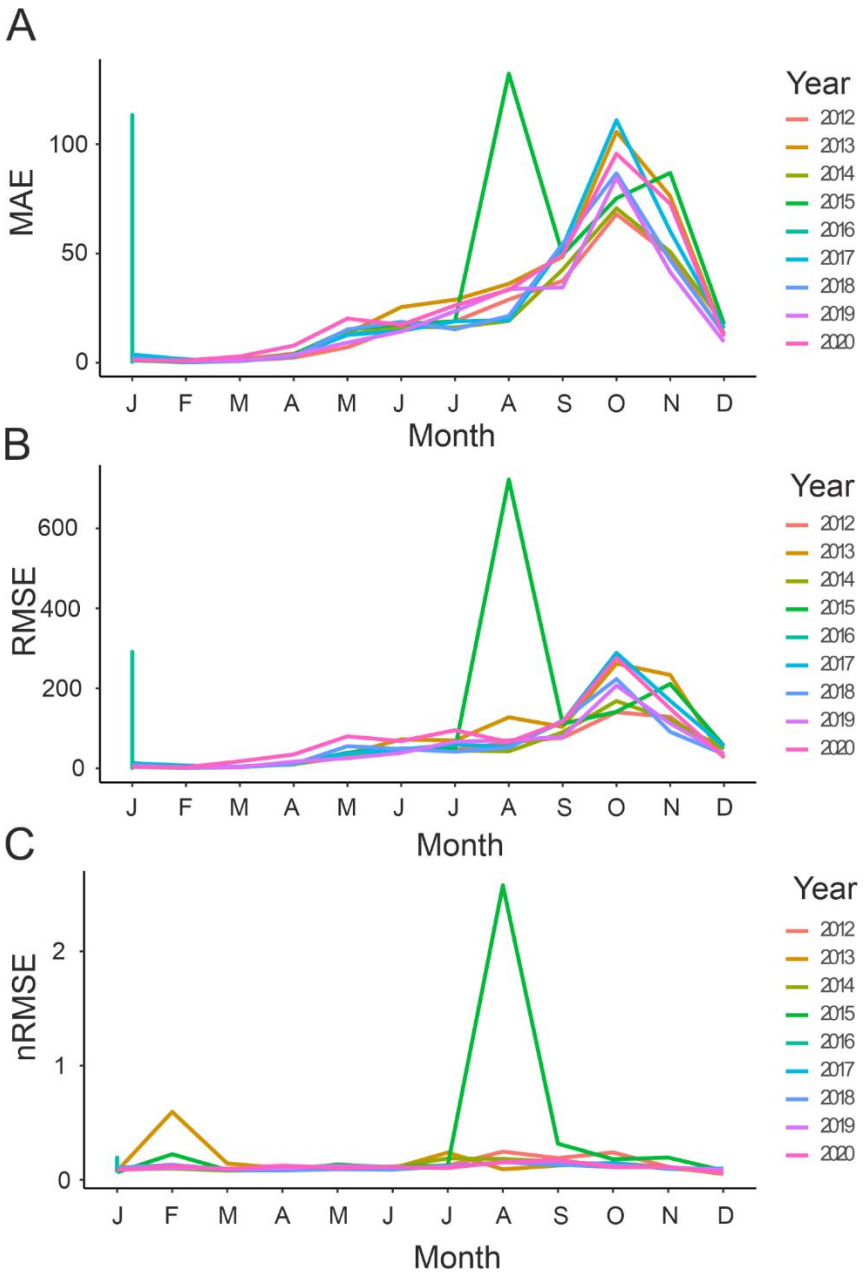



**Figure S3.** Forecast accuracy of our model for all months of each year as depicted by A) Mean Absolute Error (MAE), B) Root Mean Squared Error (RMSE), and C) Normalized Root Mean Squared Error (nRMSE). Note that MEA and RMSE are absolute measures, whereas nRMSE allows for comparison across periods 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.

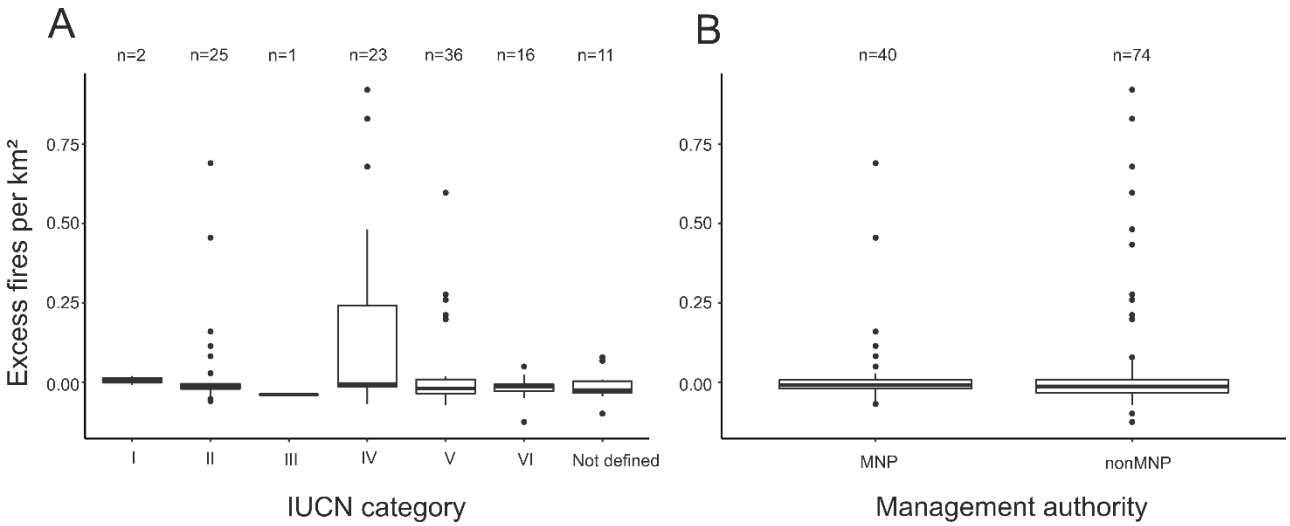



**Figure S4.** Boxplots of excess fires per km$^2$ (March-April 2020) for PAs in relation to their A) IUCN categories and B) management authority. The differences between categories are not significant as estimated by Kruskal–Wallis one-way analyses of variance (for IUCN category: chi-squared = 7.908,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

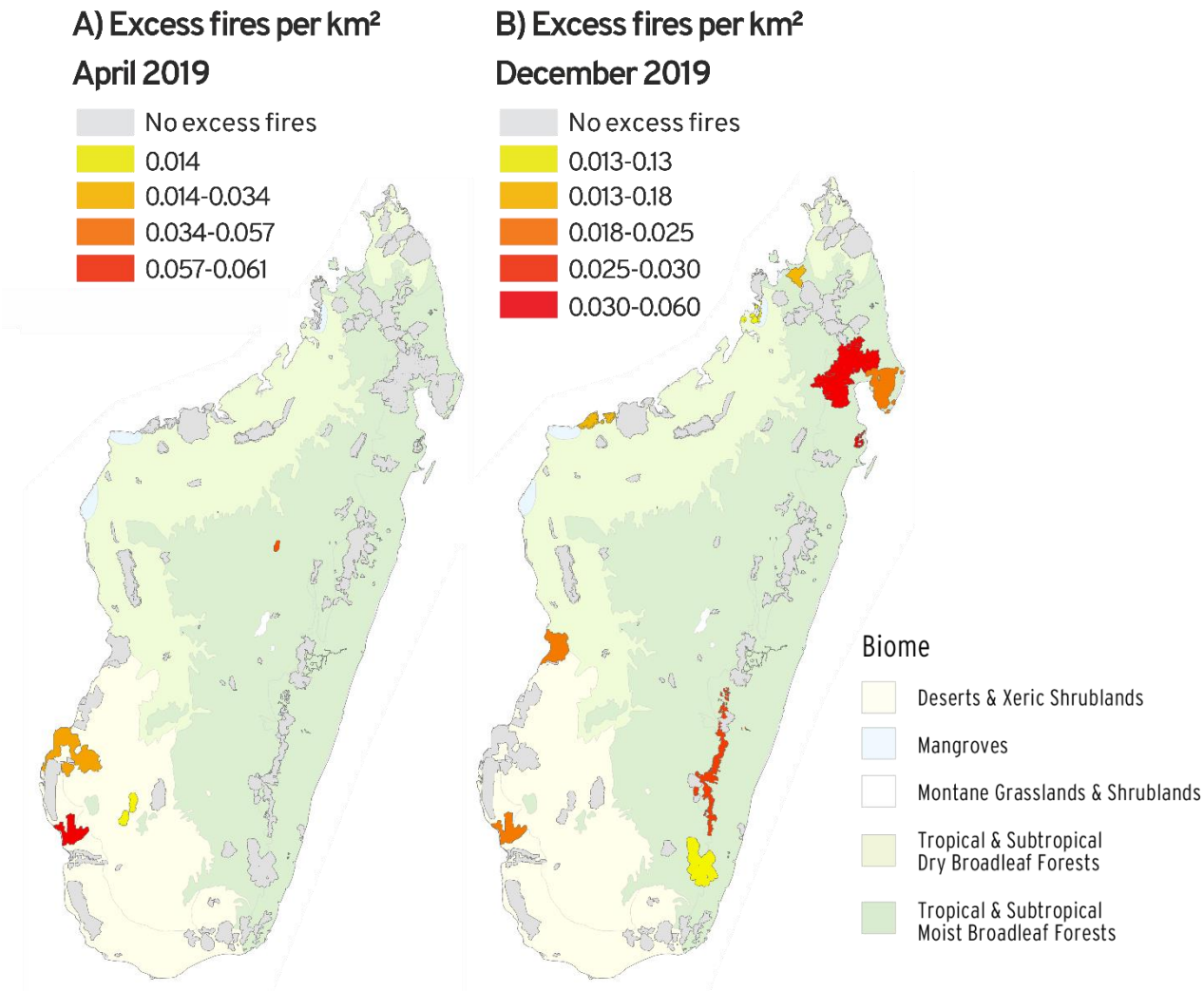



**Figure S5.** Geographical location of protected areas with excess fires in 2019 during the months with statistically more observed fires than predicted. A) April 2019 and B) December 2019.

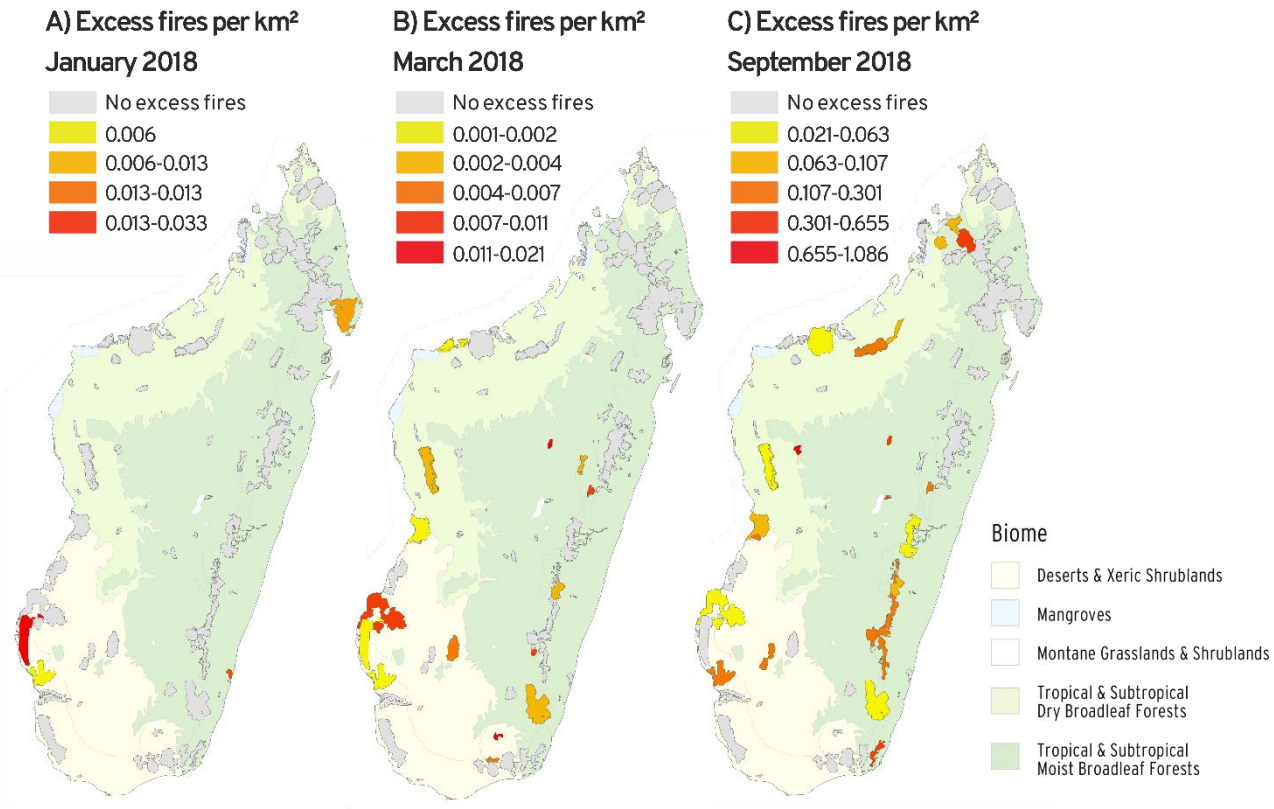



**Figure S6.** Geographical location of protected areas with excess fires in 2018 during the months with statistically more observed fires than predicted. A) January 2018, B) March 2018, C) September 2018.

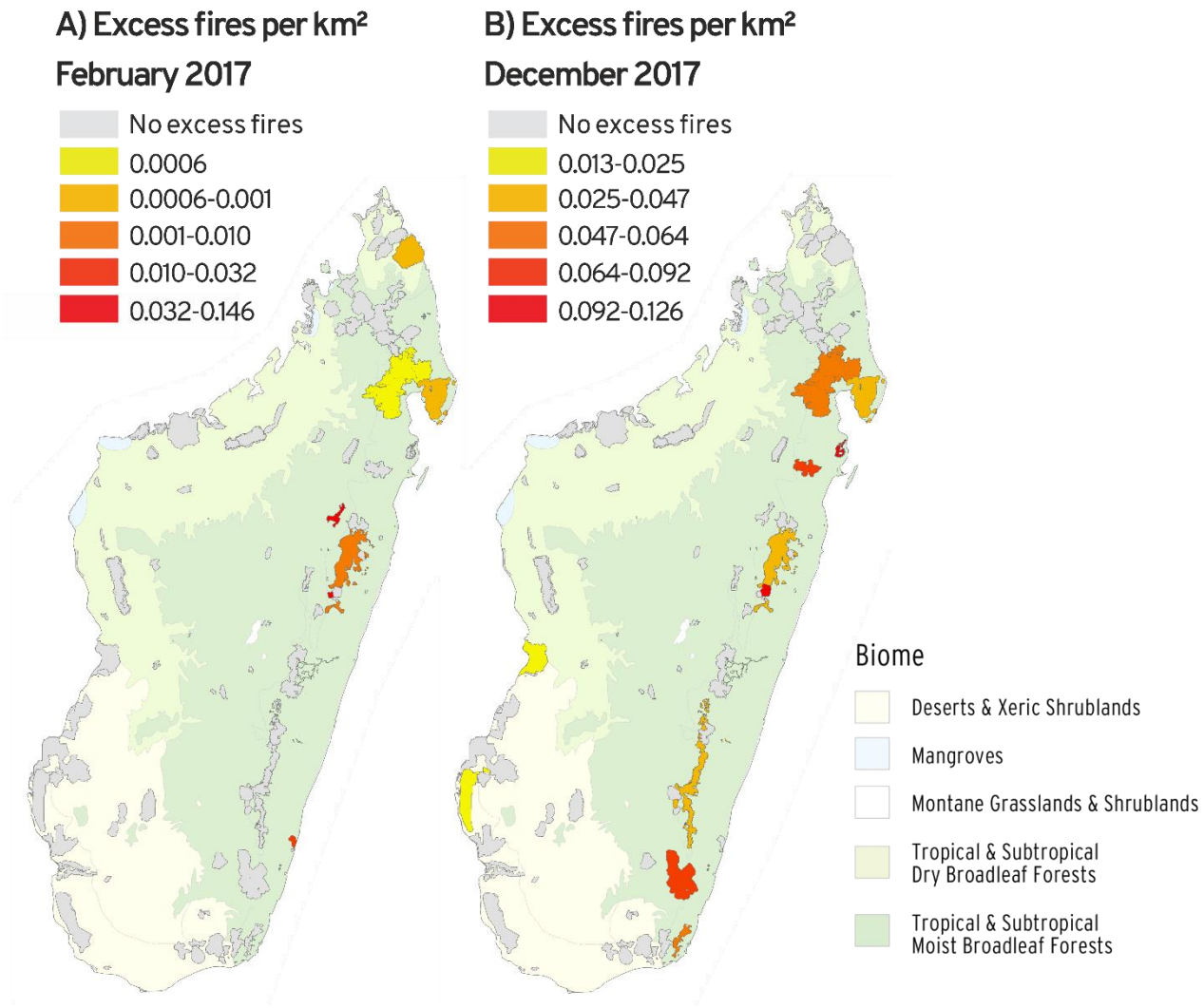



**Figure S7.** Geographical location of protected areas with excess fires in 2017 during the months with statistically more observed fires than predicted. A) February 2017 and B) December 2017.

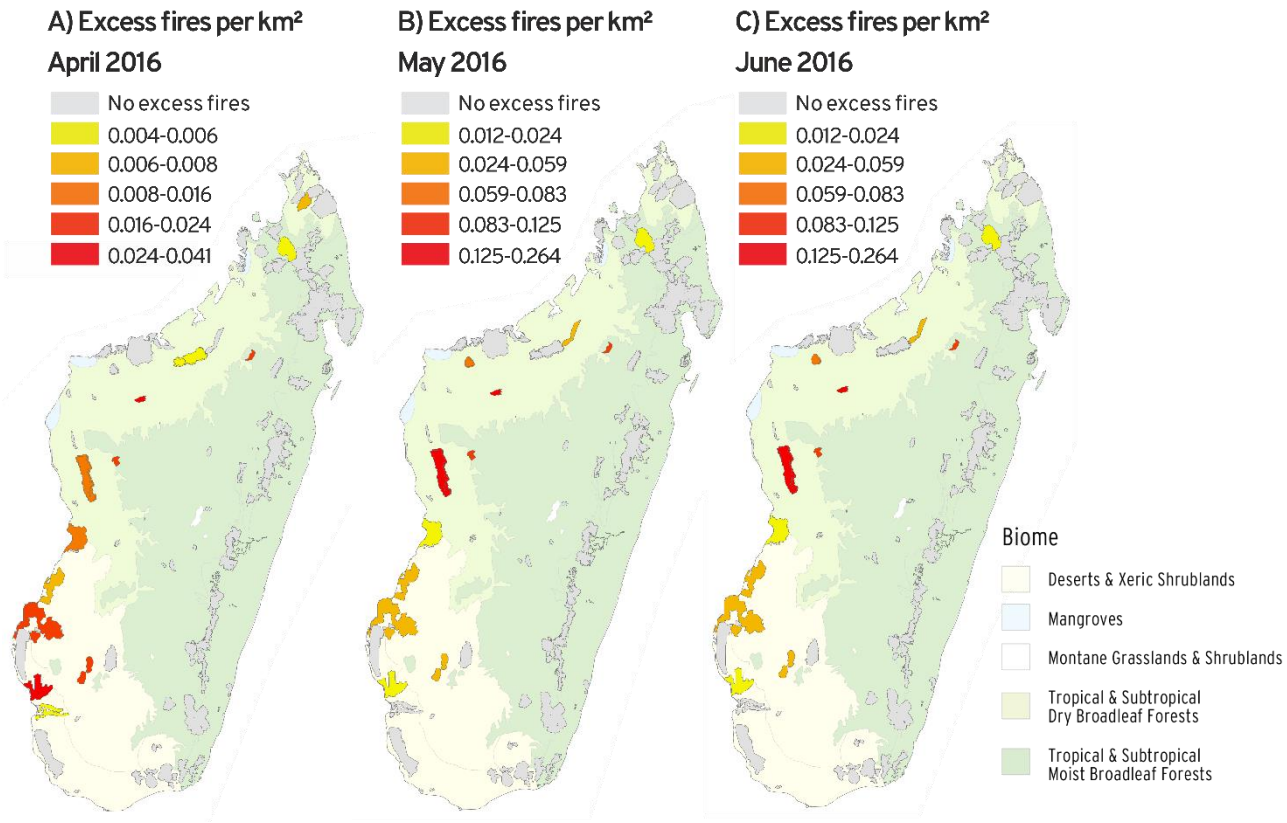



**Figure S8.** Geographical location of protected areas with excess fires in 2016 during the months with statistically more observed fires than predicted. A) April 2016, B) May 2016, C) June 2016.

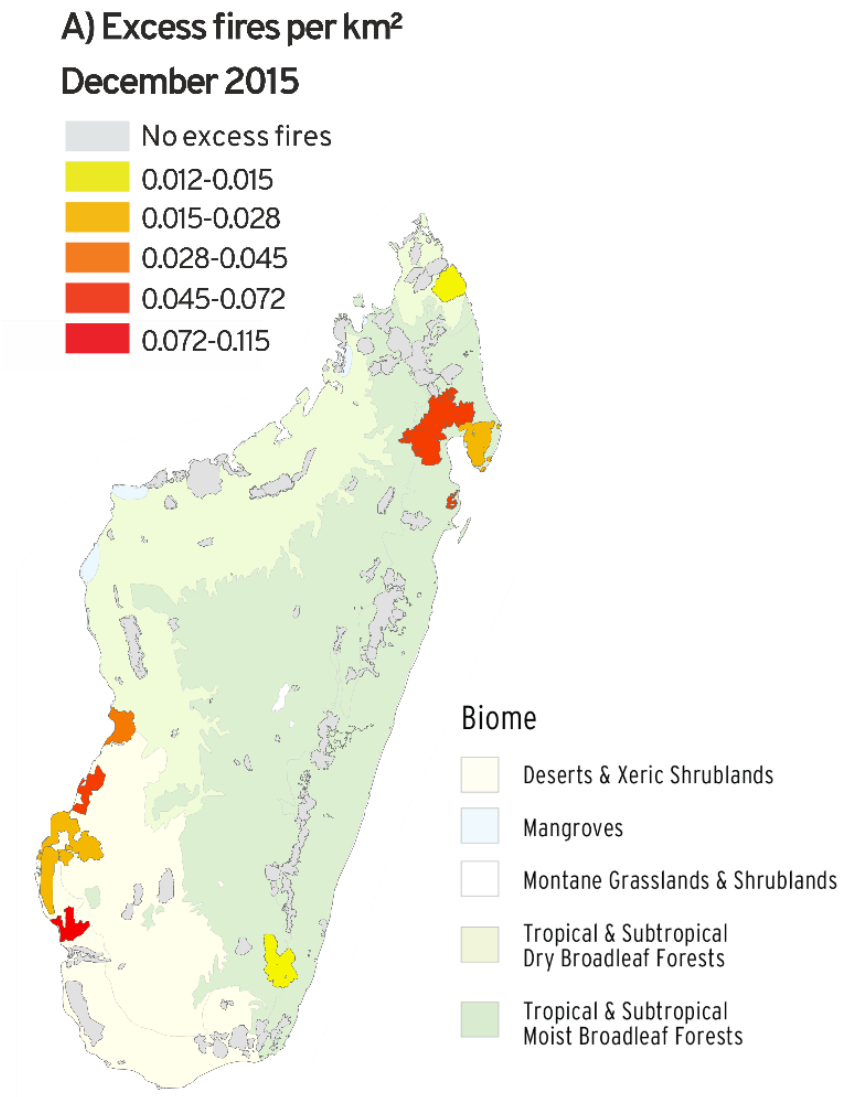



**Figure S9.** Geographical location of protected areas with excess fires in 2015 during the months with statistically more observed fires than predicted. A) December 2015.

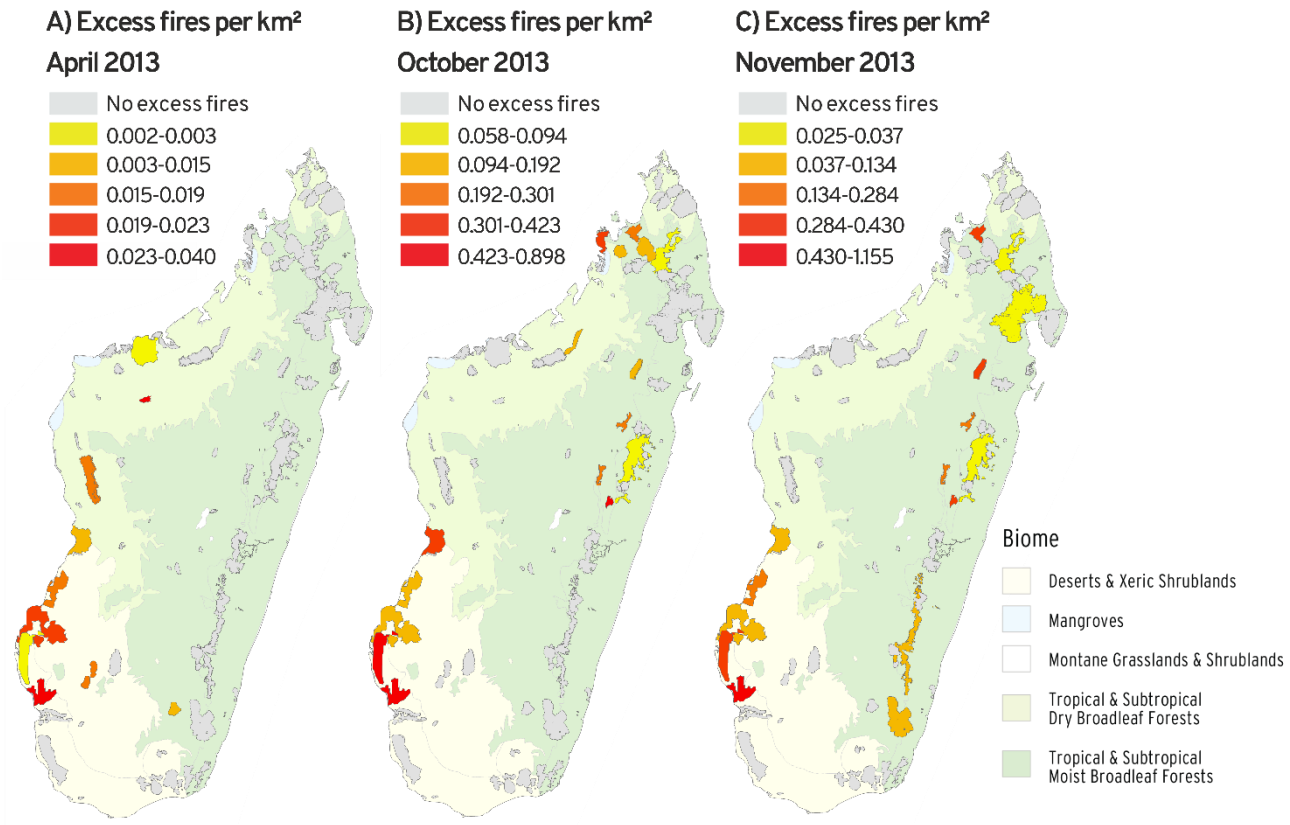



**Figure S10.** Geographical location of protected areas with excess fires in 2013 during the months with statistically more observed fires than predicted. A) April 2013, B) October 2013, C) November 2013.

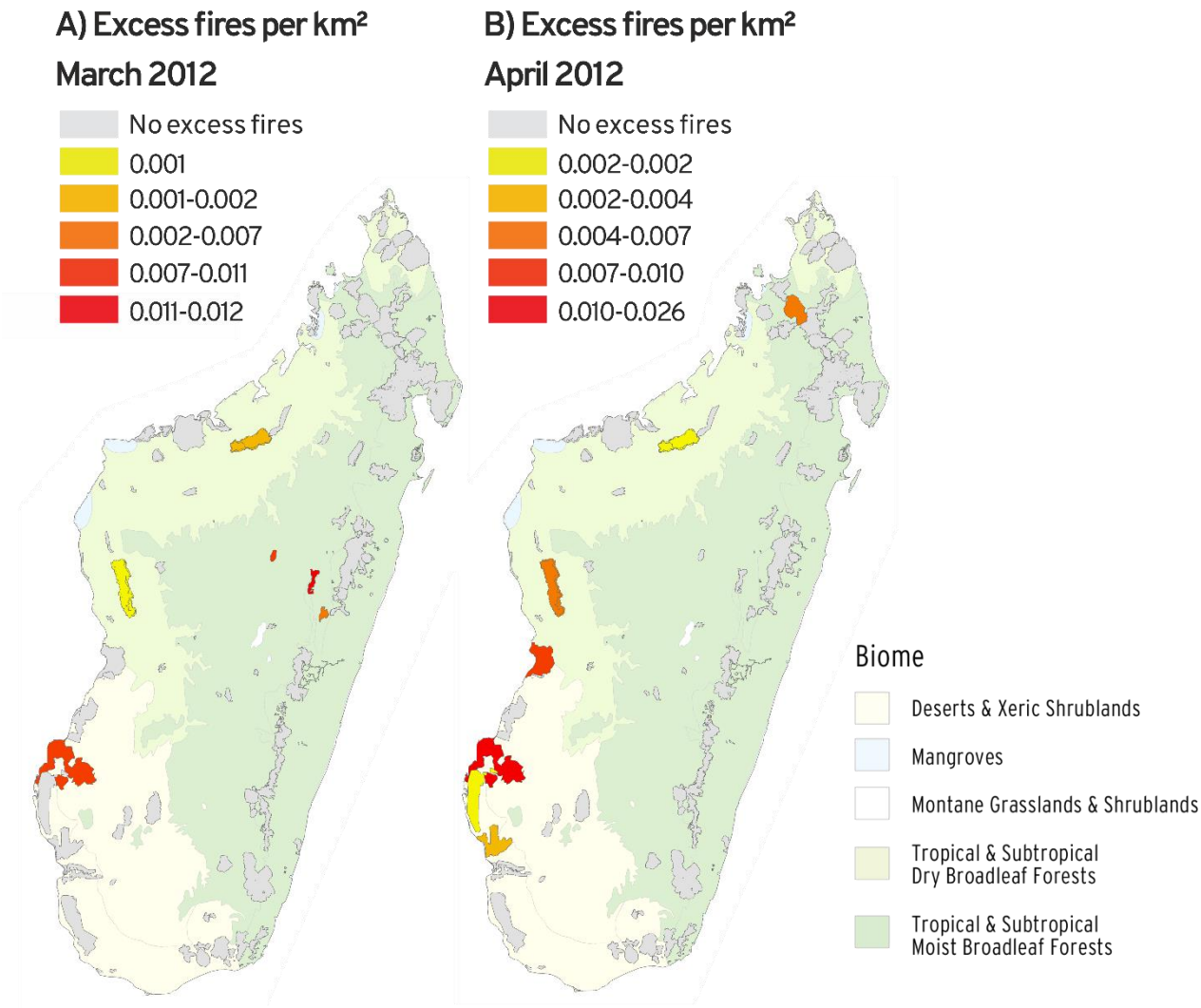



**Figure S11.** Geographical location of protected areas with excess fires in 2012 during the months with statistically more observed fires than predicted. A) March 2012 and B) April 2012.

## 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.

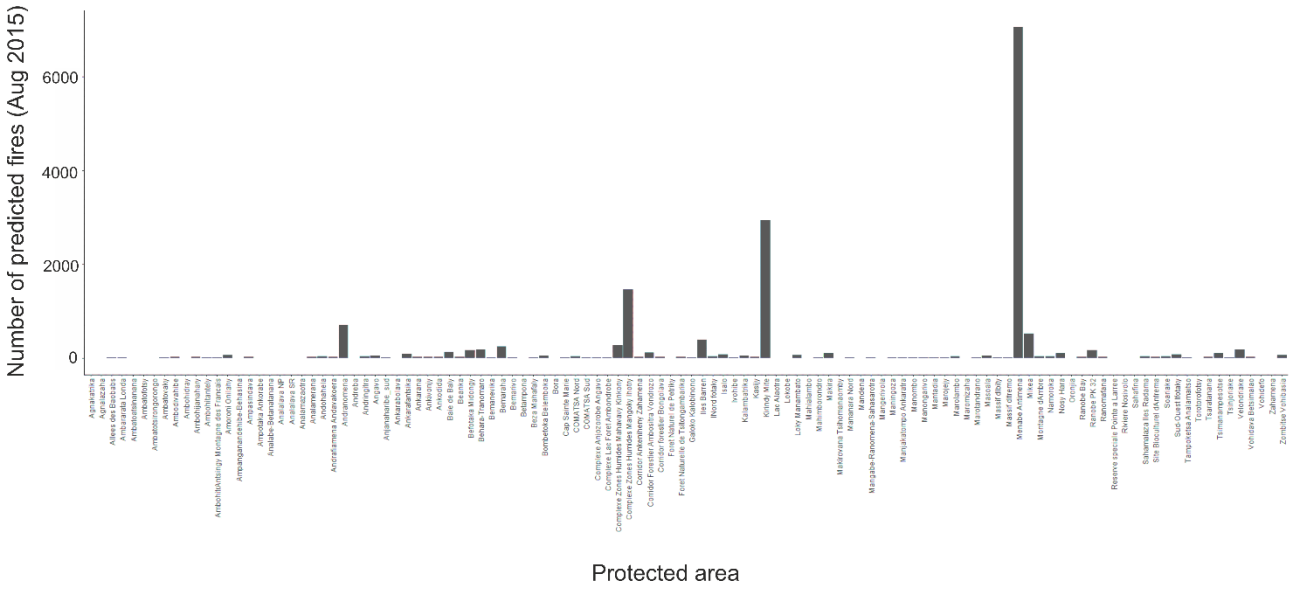



**Figure S12.** Predicted fires per protected area for August 2015.

References

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 |

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|---|---|---|---|---|
| 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 |

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|---|---|---|---|---|
| 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 | 204.3425881 | 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 |

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|---|---|---|---|---|
| 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 |