**Binturong ecology and conservation in pristine,** **fragmented and degraded tropical forests**

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Supplementary Fig. 1 Locations of the 91 camera trapping studies in 41 landscapes, as well as the analyses used for different qualities of data. (a) Study sites where camera trapping was undertaken, with black circles showing where published camera trapping studies were located and red circles showing locations of new camera trapping conducted through the Ecological Cascades Lab program (‘ECL’ hereafter, including the Pasoh site from Tropical Ecology Assessment and Monitoring or ‘TEAM’). The map inset (b) shows the process of extracting habitat covariates, which were averaged for 10-km radius around all landscape-level surveys and for the ECL datasets, these covariates were averaged for the 1-km radius around each camera. The left side of panel (c) shows the structure of the study-level species counts per landscape that was analysed using Poisson GLMMs, where the ‘landscape’ was the sampling unit. The right side of panel (s) shows the camera-level capture histories that were used in hierarchical occupancy modelling. Panel (d) summarizes the data flow from the landscape-level captures reported by published studies used in GLMMs versus the camera-level detection histories used in the occupancy modelling.

Supplementary Table 1 Description and sources of spatial data used in our analyses; For Model (S = species distribution model; L = landscape-level GLMMs, O = occupancy models; D = diel activity analyses)

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| Covariate Type | Covariate source, description or calculation | Year | | Model | Resolution | | Source hosting the layer |
| Forest cover | Natural tree cover (excluding plantations) | 2015 | S, L, O | | | 1m | CRISP-NUS1 |
| Forest edge | Distance to forest edge | 2015 | S, O, D | | | 1m | CRISP-NUS1 |
| Oil palm | Industrial plantations only, likely captures a minority of total oil palm | 2015 | S, L, O | | | 1m | CRISP-NUS1 |
| Degraded forest | Combined land cover of oil palm, lowland mosaics, lowland open ground, and regrowth/plantations | 2015 | O, D | | | 1m | CRISP-NUS1 |
| Forest integrity | Forest Landscape Integrity Index2 capturingdirect and indirect pressures on forest. | 2020 | L, O, D | | | 300m | <https://www.forestlandscapeintegrity.com> |
| Forest Intactness | Ecoregion intactness index | 2009 | S, R | | | 1km | https://doi.org/10.14264/uql.2019.773 |
| Elevation | SRTM Digital Elevation | 2020 | S, L, O | | | 30m | https://dwtkns.com/srtm30m/ |
| Land cover | MODIS classification system | 2015 | S | | | 250m | CRISP-NUS1 |
| Roughness | The mean deviance from the average altitude within a buffer (e.g., 20km), calculated from the ALOS DSM: Global 30m | 2015 | L | | | 30m | Jaxa |
| Human density | Human settlements and population | 2015 | S, L, O | | | 250m | https://ghsl.jrc.ec.europa.eu/ |
| Settlements | Overpass Turbo - OSM | 2020 | - | | | - | http://overpass-turbo.eu/ |
| Roads | OpenStreetMap | 2020 | - | | | - | https://www.openstreetmap.org |
| Rivers | GRIN - Global River Network | 2017 | O | | | - | https://www.metis.upmc.fr/en/node/375 |
| Human footprint | Human Footprint Index3 showing cumulative human pressures from direct and indirect sources. | 2009 | L, O, D | | | 1km | https://sedac.ciesin.columbia.edu/ |
| Country boundaries | Country Boundaries | 2020 | - | | | - | https://gadm.org/download\_country\_v3.html |
| Night lights | DMSP-OLS Night-time Lights | 2013 | L, S | | | 1km | https://eogdata.mines.edu/dmsp/ |
| Forest Loss | Forest Change 2000–2019 | 2019 | O | | | 30m | Global Forest Watch4 |
| Protected areas | IUCN and UNEP-WCMC, The World Database on Protected Areas (WDPA) | 2017 | 2017 | | | shape | www.protectedplanet.net |

1 (Miettinen et al., 2016)

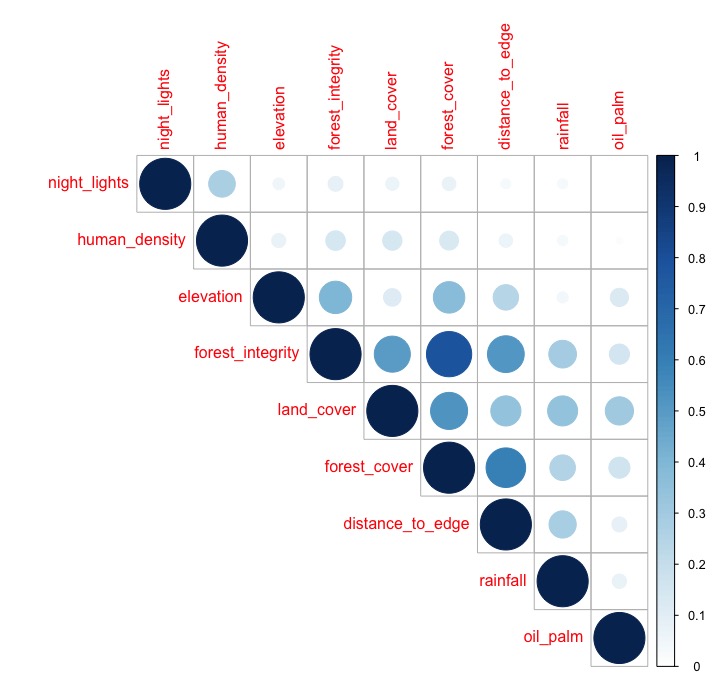
2 (Grantham et al., 2020)

3 (Venter et al., 2016)

4 <https://earthenginepartners.appspot.com/science-2013-global-forest/download_v1.7.html>

Supplementary Table 2 Study site description and effort for new camera trapping. Trap nights were estimated between the first and last photos taken for each collected camera. MCP refers to the minimum convex polygon around the camara traps. To account for variation in deployment scale and spacing, we resampled all data by grouping cameras into 1-km apothem hexagonal units (3.45 km2 cells). Therefore, the rows in the capture histories all represent the same sampling area, and because some cells had more than one camera, we included trapping effort per cell per sampling window as a covariate of detection.

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Survey | Annual rainfall | Cameras collected | Effort (trap nights) | Duration | Elevation  (mean ± SD) | Elevation range | MCP | Camera spacing |
| THAILAND |  |  |  |  |  |  |  |  |
| Khao Chong / Khao Ban Tat 2018 | 2014.28 | 76 | 3957 | 2018-02-01 – 2018-04-30 | 524.59 ± 271 | 103 – 1234 | 59.01 | 467.95 |
| Khao Yai 2019 | 1119.49 | 61 | 3553 | 2019-07-01 – 2019-09-25 | 769.64 ± 39 | 582 – 816 | 22.54 | 464.42 |
| SUMATRA |  |  |  |  |  |  |  |  |
| Gunung Leuser 2014 | 2828.00 | 69 | 3401 | 2013-12-18 – 2014-05-22 | 316.03 ± 250 | 25 – 888 | 516.15 | 1275.27 |
| Kerinci Seblat 2014 | 2406.94 | 98 | 5356 | 2014-02-10 – 2014-10-04 | 594.03 ± 194 | 252 – 1154 | 813.69 | 1169.04 |
| Bukit Barisan Selatan 2014 | 2987.80 | 79 | 5750 | 2014-06-15 – 2014-09-20 | 369.75 ± 184 | 116 – 935 | 473.58 | 1139.96 |
| MALAYSIAN BORNEO |  |  |  |  |  |  |  |  |
| Danum Valley 2019  (Sabah) | 2182.68 | 22 | 1292 | 2019-05-24 – 2019-09-26 | 256.73 ± 102 | 184 – 567 | 18.31 | 520.76 |
| Danum Valley 2018  (Sabah) | 2182.85 | 27 | 1849 | 2018-07-12 – 2018-10-30 | 249.63 ± 53 | 175 – 381 | 15.95 | 614.15 |
| Lambir Hills 2017  (Sarawak) | 3078.82 | 67 | 2406 | 2017-05-23 – 2017-07-07 | 164.80 ± 65 | 60.31 – 421.44 | 22.06 | 459.95 |
| PENINSULAR MALAYSIA |  |  |  |  |  |  |  |  |
| Pasoh 2013 | 2081.40 | 58 | 1399 | 2013-05-29 – 2014-02-12 | 297.09 ± 160 | 98 – 674 | 133.53 | 1316.26 |
| Pasoh 2014 | 2079.16 | 57 | 1314 | 2014-05-13 – 2014-08-01 | 303.14 ± 160 | 98 – 674 | 134.62 | 1321.48 |
| Pasoh 2015 | 2079.78 | 59 | 1670 | 2015-05-07 – 2015-09-04 | 301.15 ± 158 | 98 – 674 | 134.62 | 1317.78 |
| Pasoh 2016 | 2086.38 | 42 | 1305 | 2017-05-17 – 2017-08-29 | 308.98 ± 156 | 103 – 674 | 122.63 | 1416.43 |
| Ulu Muda 2015a | 2057.03 | 76 | 4242 | 2014-11-01 – 2015-01-30 | 278.58 ± 129 | 117 – 628 | 68.98 | 938.65 |
| Ulu Muda 2015b | 2063.01 | 112 | 4446 | 2015-01-31 – 2015-05-01 | 295.77 ± 140 | 117-843 | 113.61 | 731.56 |
| Ulu Muda 2015c | 2080.90 | 52 | 3582 | 2015-05-02 – 2015-07-31 | 325.38 ± 166 | 141-843 | 115.53 | 1227.86 |
| Ulu Muda 2015d | 2078.17 | 48 | 2862 | 2015-08-01 – 2015-10-30 | 328.92 ± 165 | 123-843 | 104.01 | 1237.85 |
| Ulu Muda 2016a | 2065.89 | 73 | 2220 | 2015-10-31 – 2016-01-29 | 313.62 ± 145 | 117-748 | 103.17 | 794.92 |
| Ulu Muda 2016b | 2054.55 | 60 | 2899 | 2016-01-30 – 2016-04-29 | 285.45 ± 135 | 117-628 | 66.96 | 958.39 |
| Ulu Muda 2016c | 2060.54 | 46 | 2746 | 2016-04-30 – 2016-07-22 | 301.30 ± 138 | 117-628 | 65.72 | 974.47 |
| SINGAPORE |  |  |  |  |  |  |  |  |
| Singapore 2019 | 2283.97 | 36 | 2359 | 2018-12-26 – 2019-03-17 | 41.44 ± 22.18 | 0 – 83 | 162.35 | 261.70 |



Supplementary Fig. 2 Pearson’s correlation coefficient |*r|* between initial set of predictor variables for species distribution modelling. Forest cover and integrity were the only variables that were highly correlated (> 0.7) and forest integrity was removed given its stronger correlations with the other variables than forest cover.



Supplementary Fig. 3 Projections of binturong habitat suitability of the top models for each algorithm after 10 repetitions (cropped by species IUCN range); Generalized linear model (GLM), multivariate adaptive regression splines (MARS), generalized boosted regressions model (GBM), classification tree analysis (CTA), random forest (RF), maxent (MaXent), artificial neural network (ANN) and support vector machines (SVM). Scale bar indicates a measure of intrinsic habitat suitability as determined by each algorithm (0 to 1)

Supplementary Table 3 Performance of the top models for each algorithm and the ensemble model; Generalized linear model (GLM), multivariate adaptive regression splines (MARS), generalized boosted regressions model (GBM), classification tree analysis (CTA), random forest (RF), maxent (MaXent), artificial neural network (ANN) and support vector machines (SVM). The metrics below follow the (1) TSS refers to the True Skill Statistic; (2)AUC refers to the area under the receiving operating characteristic curve; (3) Omission rate, i.e. test localities that falls into pixels not predicted as suitable (%); (4) sensitivity, i.e. true positives (both predicted and observed as present); (5) specificity, i.e. true negatives (both predicted and observed as being absent); (6) prediction success, i.e. proportion of correct predictions; and (7) Cohen’s kappa, i.e. the proportion of specific agreement.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Algorithm** | **TSS threshold** | **AUC** | **Omission rate** | **Sensitivity** | **Specificity** | **Prediction success** | **Kappa** |
| GLM | 0.121 | 0.711 | 0.167 | 0.833 | 0.588 | 0.619 | 0.197 |
| MARS | 0.114 | 0.708 | 0.167 | 0.833 | 0.582 | 0.614 | 0.193 |
| GBM | 0.127 | 0.824 | 0.119 | 0.881 | 0.767 | 0.824 | 0.647 |
| CTA | 0.455 | 0.754 | 0.19 | 0.81 | 0.698 | 0.753 | 0.506 |
| RF | 0.474 | 0.751 | 0.167 | 0.833 | 0.669 | 0.751 | 0.503 |
| MAXENT | 0.53 | 0.709 | 0.262 | 0.738 | 0.68 | 0.681 | 0.036 |
| ANN | 0.458 | 0.579 | 0.524 | 0.476 | 0.682 | 0.581 | 0.159 |
| SVM | 0.61 | 0.777 | 0.222 | 0.778 | 0.776 | 0.777 | 0.554 |
| GLM | 0.121 | 0.711 | 0.167 | 0.833 | 0.588 | 0.619 | 0.197 |
| **Ensemble** | **0.416** | **0.777** | **0.175** | **0.825** | **0.728** | **0.776** | **0.553** |

Supplementary Table 4 Range, forest cover and naïve occupancy of binturongs in Southeast Asia. IUCN refers to the species extant range, which we calculated as the total area within the IUCN Redlist range in each region (km²). Forested IUCN range is defined here as the forested area in 2015 remaining within the species IUCN range, which is an overestimate because it assumes all remaining forest is occupied. Therefore, it may be interpreted more correctly as the remaining habitat available. ‘Percent forested’ is the Forested IUCN range divided by the IUCN range and the ‘Percent protected’ is forested area within protected areas divided by the IUCN range. Protected areas were taken from Protected Planet database.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Region** | **IUCN (km2)** | **Forested IUCN range (km2)** | **Forested IUCN range (%)** | **Protected forested range (%)** | **Naïve occupancy** |
| Borneo | 733116 | 320672 | 43.7 | 6.6 | 0.67 |
| Thailand-Laos-Cambodia | 1357350 | 556422 | 41 | 14.1 | 0.50 |
| Peninsular Malaysia | 130936 | 46030 | 35.2 | 12.5 | 0.56 |
| Sumatra | 430037 | 84888 | 19.7 | 7.6 | 0.71 |
| **Total** | **2651439** | **1008012** | **38** | **10.9** | **0.60** |

\*excluding Singapore and the Philippines

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Supplementary Fig. 4 Other binturong regional habitat associations (a) Forest Cover (c) degraded against non-degraded forests, and (d) high integrity against low integrity forests.

Supplementary Table 5 Description of compiled surveys and new camera trapping sessions by landscape for regional analysis. Here we illustrate the cumulative effort and independent binturong detections across studies by landscape. We also include information on the year, country and number of studies. For landscape ID please refer to abbreviations as WS = Wildlife Sanctuary, NP = National Park, and FR =Forest Reserve.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Landscape ID | Country | Cumulative detections | Cumulative effort | Year | Number of studies/sessions | Sampled points |
| Phnom Prich WS | Cambodia | 0 | 7295 | 2009 | 2 | 768 |
| Southern Cardamom NP | Cambodia | 0 | 8236 | 2015 | 1 | 5164 |
| Kerinci Seblat | Indonesia | 24 | 46880 | 2006-2015 | 11 | 97 |
| Riau Province | Indonesia | 6 | 7513 | 2005 | 1 | 2142 |
| Bukit Barisan Selatan | Indonesia | 6 | 11442 | 2014 | 3 | 126 |
| Gunung Leuser | Indonesia | 5 | 3531 | 2014 | 1 | 522 |
| Batang Gadis NP | Indonesia | 2 | 1728 | 2004 | 1 | 432 |
| Sabangau | Indonesia | 1 | 22588 | 2008 | 1 | 57 |
| Asiatic Persada | Indonesia | 0 | 7102 | 2005 | 1 | 630 |
| Taratak Sungai Lundang | Indonesia | 0 | 2720 | 2005 | 1 | 522 |
| Nam Kading | Laos | 15 | 4344 | 2009-2014 | 6 | 1395 |
| Ulu Muda | Malaysia | 33 | 22997 | 2014-2016 | 3 | 1690 |
| Perak | Malaysia | 21 | 25904 | 2012 | 1 | 775 |
| Pasoh | Malaysia | 8 | 20209 | 2013-2018 | 6 | 3111 |
| Maliau | Malaysia | 5 | 8038 | 2010 | 1 | 2808 |
| Ulu Baram | Malaysia | 5 | 1410 | 2012 | 1 | 5372 |
| Lambir Hills NP | Malaysia | 5 | 3412 | 2004; 2017 | 2 | 896 |
| Terengganu | Malaysia | 5 | 37846 | 2011-2012 | 2 | 119 |
| Deramakot FR | Malaysia | 3 | 551 | 2006 | 1 | 1222 |
| Imbak Canyon Conservation Area | Malaysia | 3 | 1436 | 2012 | 1 | 374 |
| Gunung Basor FR | Malaysia | 2 | 2664 | 2004 | 1 | 816 |
| Tangkulap FR | Malaysia | 2 | 272 | 2006 | 1 | 2262 |
| Danum Valley | Malaysia | 2 | 6950 | 2013-2019 | 4 | 9898 |
| Bintulu acacia | Malaysia | 1 | 5679 | 2005 | 1 | 2310 |
| Ulu Padas | Malaysia | 1 | 1717 | 2011 | 1 | 2416 |
| Mulu | Malaysia | 0 | 2315 | 2010 | 1 | 336 |
| Pulong Tau | Malaysia | 0 | 3217 | 2010 | 1 | 3744 |
| Hose mountains | Malaysia | 0 | 1499 | 2012 | 1 | 3483 |
| Ulu Trusan | Malaysia | 0 | 1132 | 2012 | 1 | 344 |
| Krau | Malaysia | 0 | 1024 | 2013 | 2 | 1178 |
| Ulu Segama | Malaysia | 0 | 2153 | 2013 | 2 | 96 |
| Singapore Sentosa S Ridges | Singapore | 0 | 1401 | 2019 | 1 | 325 |
| Singapore CCNR | Singapore | 0 | 125577 | 2010-2019 | 15 | 1748 |
| Singapore Pulau Ubin | Singapore | 0 | 6291 | 2013-2014; 2019 | 3 | 84 |
| Khlong Saeng WS | Thailand | 13 | 10236 | 2014 | 1 | 120 |
| Hala-bala WS | Thailand | 7 | 11106 | 2004 | 1 | 1360 |
| Khao Yai NP | Thailand | 4 | 10664 | 2003; 2019 | 2 | 765 |
| KhaoChong | Thailand | 2 | 4823 | 2018 | 1 | 1458 |
| Ta Phraya NP | Thailand | 0 | 1193 | 2009 | 1 | 684 |
| Don Yai WS | Thailand | 0 | 563 | 2012 | 1 | 1144 |
| Huai Kha Khaeng WS | Thailand | 0 | 15388 | 2017 | 2 | 378 |
| Total | - | 181 | 461046 | - | 91 | 63171 |

Supplementary Table 6 New camera trapping effort and landscape-level naïve occupancy of the binturong (Arctictis binturong) by country. Camera trapping studies were grouped into ‘landscapes’, which were usually national parks or other defined forests separated by a hard border (agriculture, urban areas). The landscapes were considered to be occupied if our study species was ever captured there, regardless of the time of sampling. Some landscapes have repeated samples, which is why the total studies available for the GLMM exceeds the number of landscapes presented here. RAI is the relative abundance index, calculated as the independent captures per 100 trap nights.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Region** | **Study** | **Year** | **Independent captures** | **Total effort (trap nights)** | **Number of camera trap** | **Naïve occupancy** | **RAI** |
| Peninsular Malaysia | Ulu Muda (b) | 2015 | 12 | 4446 | 112 | 0.093 | 0.269 |
| Peninsular Malaysia | Ulu Muda (a) | 2016 | 7 | 2220 | 73 | 0.102 | 0.315 |
| Peninsular Malaysia | Ulu Muda (a) | 2015 | 6 | 4242 | 76 | 0.089 | 0.141 |
| Peninsular Malaysia | Gunung Leuser | 2014 | 5 | 3401 | 69 | 0.072 | 0.147 |
| Peninsular Malaysia | Ulu Muda (b) | 2016 | 4 | 2899 | 60 | 0.073 | 0.138 |
| Sumatra | Bukit Barisan Selatan | 2014 | 3 | 5750 | 79 | 0.038 | 0.052 |
| Sumatra | Kerinci Seblat | 2014-2015 | 3 | 5356 | 98 | 0.0546 | 0.056 |
| Sarawak | Lambir Hills | 2017 | 3 | 2406 | 67 | 0.097 | 0.125 |
| Thailand | Khao Chong | 2018 | 2 | 3957 | 76 | 0.045 | 0.051 |
| Peninsular Malaysia | Ulu Muda (d) | 2015 | 2 | 2862 | 48 | 0.021 | 0.069 |
| Sabah | Danum Valley (a) | 2019 | 1 | 1292 | 22 | 0.077 | 0.077 |
| Sabah | Danum Valley | 2018 | 1 | 1849 | 27 | 0.053 | 0.054 |
| Thailand | Khao Yai | 2019 | 1 | 3553 | 61 | 0.032 | 0.028 |
| Peninsular Malaysia | Pasoh | 2015 | 1 | 1670 | 59 | 0.017 | 0.059 |
| Peninsular Malaysia | Pasoh | 2017 | 1 | 1305 | 42 | 0.024 | 0.077 |
| Peninsular Malaysia | Ulu Muda (c) | 2015 | 1 | 3582 | 52 | 0.019 | 0.028 |
| Peninsular Malaysia | Ulu Muda (c) | 2016 | 1 | 2746 | 46 | 0.024 | 0.036 |
| Peninsular Malaysia | Pasoh | 2013 | 0 | 1399 | 58 | 0 | 0 |
| Peninsular Malaysia | Pasoh | 2014 | 0 | 1314 | 57 | 0 | 0 |
| Singapore | Singapore | 2018-2019 | 0 | 2359 | 36 | 0 | 0 |

Supplementary Table 7 Model estimates and significance for assessing local (within-site) variation in binturong occupancy. No multivariate models improved performance by >2 AICc points from the Null/reduced model, which contained the sampling unit effort as a covariate in the detection formula and the trapping session as covariate affecting occupancy, which were included in all models. Variables with models which performed worse than the Null/reduced model based on AICc selection were excluded from the manuscript.

|  |  |  |  |
| --- | --- | --- | --- |
| **Variable included** | **Estimate** | **SE** | **P** |
| Elevation | 2.35 | 1.12 | **0.035** |
| Distance to river | 0.798 | 0.502 | 0.112 |
| Oil palm | -0.796 | 0.677 | 0.240 |
| Null/reduced model | NA | NA | NA |
| Forest cover | 0.336 | 0.392 | 0.391 |
| Forest loss | 0.318 | 0.405 | 0.433 |
| Human footprint | -0.181 | 0.346 | 0.602 |
| Distance to forest edge | -0.255 | 0.614 | 0.678 |
| Forest integrity | -0.146 | 0.561 | 0.794 |
| Human population density | 0.074 | 0.334 | 0.825 |

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Supplementary Fig. 5 Binturong activity patterns and variation across disturbance variables (a) and (b) illustrate the density of activity patterns and independent captures, respectively. After excluding sites with <4 captures, we illustrate the activity pattern association between disturbance variables of (c) degraded against non-degraded forests, and (d) high integrity against low integrity forests (FILI <500).

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Supplementary Fig. 6 Binturong activity pattern in association to human activity patterns The density of human activity was categorised into (a) researchers, (b) tourists, (c) hikers, and (d) rangers. An aggregated pattern for all human activity is illustrated in (e).

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