

## Supplementary Materials

Supplementary Table S1. Environmental variables

<b>Variable Name</b>	<b>Description</b>	<b>Resolution</b>
(Bio1) Annual Mean Temperature	Mean of all monthly temperature values	1km
(Bio2) Mean Diurnal Range	Mean of monthly (max temp - min temp)	1km
(Bio3) Isothermality	$(\text{Bio2} / \text{Bio7}) \times 100$	1km
(Bio4) Temperature Seasonality	Standard deviation of monthly temperature $\times 100$	1km
(Bio5) Max Temperature of Warmest Month	Highest monthly max temperature	1km
(Bio6) Min Temperature of Coldest Month	Lowest monthly min temperature	1km
(Bio7) Temperature Annual Range	Bio5 - Bio6	1km
(Bio8) Mean Temperature of Wettest Quarter*	Average temperature during wettest 3 months	1km
(Bio9) Mean Temperature of Driest Quarter*	Average temperature during driest 3 months	1km
(Bio10) Mean Temperature of Warmest Quarter	Average temperature during warmest 3 months	1km
(Bio11) Mean Temperature of Coldest Quarter	Average temperature during coldest 3 months	1km
(Bio12) Annual Precipitation	Sum of monthly precipitation	1km
(Bio13) Precipitation of Wettest Month	Precipitation of the month with highest rainfall	1km
(Bio14) Precipitation of Driest Month	Precipitation of the month with lowest rainfall	1km
(Bio15) Precipitation Seasonality	Coefficient of Variation of monthly precipitation	1km
(Bio16) Precipitation of Wettest Quarter	Total precipitation during wettest 3 months	1km
(Bio17) Precipitation of Driest Quarter	Total precipitation during driest 3 months	1km
(Bio18) Precipitation of Warmest Quarter*	Total precipitation during warmest 3 months	1km
(Bio19) Precipitation of Coldest Quarter*	Total precipitation during coldest 3 months	1km
MODIS Normalized Difference Vegetation Index (NDVI)	September – April (2011 - 2024) (16-day)	1km
Elevation (m)	Elevation refers to the height above sea level (meters).	1km

Slope (%)	Slope measures the steepness or gradient of the terrain, typically expressed in degrees or percent rise.	1km
Topographic Wetness Index (TWI)	Quantify how local terrain influences water accumulation.	1km
Topographic Roughness Index (TRI)	Quantifies local terrain ruggedness.	1km

**Supplementary Table S2. Plague Occurrence Cases (1939-2023)**

Type	Year	Longitude	Latitude	Reference
Human	2023	47.268607	-18.723889	Agrawal, R., Murmu, J., Pattnaik, S., Kanungo, S., & Pati, S. (2023). One Health: navigating plague in Madagascar amidst COVID-19. <i>Infectious Diseases of Poverty</i> , 12(1), 50.
Human	2023	47.757131	-19.256629	Agrawal, R., Murmu, J., Pattnaik, S., Kanungo, S., & Pati, S. (2023). One Health: navigating plague in Madagascar amidst COVID-19. <i>Infectious Diseases of Poverty</i> , 12(1), 50.
Dog	2022	49.388845	-18.103161	Tracking of Mammals and Their Fleas for Plague Surveillance in Madagascar, 2018–2019
Human	2021	46.947859	-19.40824	<a href="https://www.who.int/news-room/articles-detail/plague---madagascar">https://www.who.int/news-room/articles-detail/plague---madagascar</a>
Human	2021	48.423899	-17.823378	<a href="https://www.who.int/news-room/articles-detail/plague---madagascar">https://www.who.int/news-room/articles-detail/plague---madagascar</a>
Human	2021	47.453875	-18.807695	<a href="https://www.who.int/news-room/articles-detail/plague---madagascar">https://www.who.int/news-room/articles-detail/plague---madagascar</a>
Human	2021	46.479047	-18.688805	Transmission of Antimicrobial Resistant <i>Yersinia pestis</i> During a Pneumonic Plague Outbreak
Human	2021	47.052946	-19.556024	Transmission of Antimicrobial Resistant <i>Yersinia pestis</i> During a Pneumonic Plague Outbreak
Human	2021	45.967914	-18.985236	Transmission of Antimicrobial Resistant <i>Yersinia pestis</i> During a Pneumonic Plague Outbreak
Flea	2020	47.186536	-18.103635	Presence of the Oriental Rat Flea (Siphonaptera: Pulicidae) Infesting an Endemic Mammal and Confirmed Plague Circulation in a Forest Area of Madagascar
Human	2017	49.379433	-18.152442	Epidemiological characteristics of an urban plague epidemic in Madagascar, August–November, 2017: an outbreak report
Human	2017	46.057016	-18.770684	A decade of plague in Madagascar: a description of two hotspot districts
Human	2017	46.982416	-23.826669	<a href="https://www.who.int/emergencies/disease-outbreak-news/item/09-january-2017-plague-mdg-en">https://www.who.int/emergencies/disease-outbreak-news/item/09-january-2017-plague-mdg-en</a>
Human	2017	47.593148	-19.100425	<a href="https://www.who.int/emergencies/disease-outbreak-news/item/29-september-2017-plague-madagascar-en">https://www.who.int/emergencies/disease-outbreak-news/item/29-september-2017-plague-madagascar-en</a>
Human	2017	46.926492	-21.836739	<a href="https://www.who.int/news-room/articles-detail/plague---madagascar">https://www.who.int/news-room/articles-detail/plague---madagascar</a>
Human	2017	50.008982	-13.363933	<a href="https://www.who.int/news-room/articles-detail/plague---madagascar">https://www.who.int/news-room/articles-detail/plague---madagascar</a>
Human	2017	47.15645	-19.643822	Multiple Introductions of <i>Yersinia pestis</i> during Urban Pneumonic Plague Epidemic
Human	2017	47.112585	-18.31408	Multiple Introductions of <i>Yersinia pestis</i> during Urban Pneumonic Plague Epidemic, Madagascar, 2017
Human	2017	47.188571	-19.274869	Multiple Introductions of <i>Yersinia pestis</i> during Urban Pneumonic Plague Epidemic, Madagascar, 2017

Human	2017	46.729641	-18.884712	Multiple Introductions of Yersinia pestis during Urban Pneumonic Plague Epidemic Madagascar, 2017
Human	2017	46.902812	-18.958559	Multiple Introductions of Yersinia pestis during Urban Pneumonic Plague Epidemic, Madagascar, 2017
Human	2017	47.131579	-18.96751	Multiple Introductions of Yersinia pestis during Urban Pneumonic Plague Epidemic, Madagascar, 2017
Human	2017	47.896978	-18.795272	Multiple Introductions of Yersinia pestis during Urban Pneumonic Plague Epidemic, Madagascar, 2017
Human	2017	46.004035	-19.362393	Multiple Introductions of Yersinia pestis during Urban Pneumonic Plague Epidemic, Madagascar, 2017
Human	2016	46.103538	-18.767874	Bubonic Plague Outbreak Investigation in the Endemic District of Tsiroanomandidy - Madagascar, October 2014
Human	2016	46.120355	-18.788746	Bubonic Plague Outbreak Investigation in the Endemic District of Tsiroanomandidy - Madagascar, October 2014
Human	2016	46.054045	-18.751694	Bubonic Plague Outbreak Investigation in the Endemic District of Tsiroanomandidy - Madagascar, October 2014
Human	2016	45.870827	-18.516484	Bubonic Plague Outbreak Investigation in the Endemic District of Tsiroanomandidy - Madagascar, October 2014
Human	2016	46.18789	-18.703272	Bubonic Plague Outbreak Investigation in the Endemic District of Tsiroanomandidy - Madagascar, October 2014
Human	2016	46.310432	-18.680072	Bubonic Plague Outbreak Investigation in the Endemic District of Tsiroanomandidy - Madagascar, October 2014
Human	2016	46.127095	-18.908144	Bubonic Plague Outbreak Investigation in the Endemic District of Tsiroanomandidy - Madagascar, October 2014
Human	2016	46.115673	-18.906359	Bubonic Plague Outbreak Investigation in the Endemic District of Tsiroanomandidy - Madagascar, October 2014
Human	2016	46.183634	-18.919506	Bubonic Plague Outbreak Investigation in the Endemic District of Tsiroanomandidy - Madagascar, October 2014
Human	2016	46.367444	-18.971618	Bubonic Plague Outbreak Investigation in the Endemic District of Tsiroanomandidy - Madagascar, October 2014
Human	2016	46.321402	-18.933823	Bubonic Plague Outbreak Investigation in the Endemic District of Tsiroanomandidy - Madagascar, October 2014
Human	2016	46.323757	-18.923134	Bubonic Plague Outbreak Investigation in the Endemic District of Tsiroanomandidy - Madagascar, October 2014
Human	2016	46.266336	-18.946967	Bubonic Plague Outbreak Investigation in the Endemic District of Tsiroanomandidy - Madagascar, October 2014
Human	2015	47.666855	-17.265737	Riehm JM, Projahn M, Vogler AJ, Rajerison M, Andersen G, Hall CM, et al. Diverse Genotypes of Yersinia pestis Caused Plague in Madagascar in 2007. PLoS neglected tropical diseases. 2015;9(6):e0003844. pmid:26069964;.
Human	2015	48.221013	-18.92862	<a href="https://www.who.int/emergencies/disease-outbreak-news/item/06-september-2015-plague-en">https://www.who.int/emergencies/disease-outbreak-news/item/06-september-2015-plague-en</a>
Human	2015	47.133647	-20.917704	Diverse Genotypes of Yersinia pestis Caused Plague in Madagascar in 2007
Human	2015	47.733803	-18.847391	Diverse Genotypes of Yersinia pestis Caused Plague in Madagascar in 2007
Human	2014	46.327124	-18.847149	<a href="https://www.who.int/emergencies/disease-outbreak-news/item/21-november-2014-plague-en">https://www.who.int/emergencies/disease-outbreak-news/item/21-november-2014-plague-en</a>
Flea	2014	46.91363	-20.381475	Yersinia pestis in Pulex irritans Fleas during Plague Outbreak, Madagascar
Human	2013	48.564106	-17.012463	Understanding the Persistence of Plague Foci in Madagascar
Human	2013	48.832798	-15.841235	Understanding the Persistence of Plague Foci in Madagascar

Human	2011	49.051192	-13.190069	Understanding the Persistence of Plague Foci in Madagascar
Human	2011	48.441924	-19.179169	Temporal phylogeography of <i>Yersinia pestis</i> in Madagascar: Insights into the long-term maintenance of plague
Human	2011	48.416792	-18.945407	Temporal phylogeography of <i>Yersinia pestis</i> in Madagascar: Insights into the long-term maintenance of plague
Human	2010	48.325582	-18.973543	Temporal phylogeography of <i>Yersinia pestis</i> in Madagascar: Insights into the long-term maintenance of plague
Human	2010	47.593482	-18.361111	Temporal phylogeography of <i>Yersinia pestis</i> in Madagascar: Insights into the long-term maintenance of plague
Human	2007	48.208606	-19.437395	Temporal phylogeography of <i>Yersinia pestis</i> in Madagascar: Insights into the long-term maintenance of plague
Human	2007	47.551561	-17.035303	Riehm JM, Projahn M, Vogler AJ, Rajerison M, Andersen G, Hall CM, et al. Diverse Genotypes of <i>Yersinia pestis</i> Caused Plague in Madagascar in 2007. PLoS neglected tropical diseases. 2015;9(6):e0003844. pmid:26069964;.
Human	2007	47.833956	-17.616026	Riehm JM, Projahn M, Vogler AJ, Rajerison M, Andersen G, Hall CM, et al. Diverse Genotypes of <i>Yersinia pestis</i> Caused Plague in Madagascar in 2007. PLoS neglected tropical diseases. 2015;9(6):e0003844. pmid:26069964;.
Human	2007	47.330144	-22.134015	Riehm JM, Projahn M, Vogler AJ, Rajerison M, Andersen G, Hall CM, et al. Diverse Genotypes of <i>Yersinia pestis</i> Caused Plague in Madagascar in 2007. PLoS neglected tropical diseases. 2015;9(6):e0003844. pmid:26069964;.
Human	2007	45.82049	-19.095526	Diverse Genotypes of <i>Yersinia pestis</i> Caused Plague in Madagascar in 2007
Human	2007	48.215004	-17.610181	Diverse Genotypes of <i>Yersinia pestis</i> Caused Plague in Madagascar in 2007
Human	2007	47.659798	-17.930149	Diverse Genotypes of <i>Yersinia pestis</i> Caused Plague in Madagascar in 2007
Human	2007	47.850571	-18.298248	Diverse Genotypes of <i>Yersinia pestis</i> Caused Plague in Madagascar in 2007
Human	2007	47.778537	-18.929142	Diverse Genotypes of <i>Yersinia pestis</i> Caused Plague in Madagascar in 2007
Human	2007	47.010528	-18.646468	Diverse Genotypes of <i>Yersinia pestis</i> Caused Plague in Madagascar in 2007
Human	2007	47.710695	-18.617209	Diverse Genotypes of <i>Yersinia pestis</i> Caused Plague in Madagascar in 2007
Human	2007	46.86731	-20.871298	Diverse Genotypes of <i>Yersinia pestis</i> Caused Plague in Madagascar in 2007
Human	2007	46.637043	-21.584334	Diverse Genotypes of <i>Yersinia pestis</i> Caused Plague in Madagascar in 2007
Human	2007	46.94893	-21.881812	Diverse Genotypes of <i>Yersinia pestis</i> Caused Plague in Madagascar in 2007
Human	2007	46.950442	-22.011635	Diverse Genotypes of <i>Yersinia pestis</i> Caused Plague in Madagascar in 2007
Human	2007	46.869214	-21.831932	Diverse Genotypes of <i>Yersinia pestis</i> Caused Plague in Madagascar in 2007
Human	2007	47.059497	-18.572806	Diverse Genotypes of <i>Yersinia pestis</i> Caused Plague in Madagascar in 2007

Human	2007	47.323616	-20.423695	Diverse Genotypes of Yersinia pestis Caused Plague in Madagascar in 2007
Human	2007	47.164589	-19.449298	Temporal phylogeography of Yersinia pestis in Madagascar: Insights into the long-term maintenance of plague
Human	2007	46.966349	-20.85249	Diverse Genotypes of Yersinia pestis Caused Plague in Madagascar in 2007
Human	2007	48.245204	-19.150049	Diverse Genotypes of Yersinia pestis Caused Plague in Madagascar in 2007
Rattus Norvegicus	2003	48.29728	-18.597512	Temporal phylogeography of Yersinia pestis in Madagascar: Insights into the long-term maintenance of plague
Human	2003	47.001399	-19.30624	Temporal phylogeography of Yersinia pestis in Madagascar: Insights into the long-term maintenance of plague
Human	2001	46.47986	-19.602175	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	2001	47.796655	-18.683258	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	2001	47.301641	-20.601147	Vogler AJ, Chan F, Wagner DM, Roumagnac P, Lee J, Nera R, et al. Phylogeography and Molecular Epidemiology of Yersinia pestis in Madagascar. PLoS neglected tropical diseases. 2011;5(9):e1319. Epub 2011/09/21. pmid:21931876
Human	2000	46.857087	-21.3321	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	2000	47.690854	-18.867147	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	2000	46.618515	-19.251464	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	2000	46.904086	-20.326486	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	2000	46.719502	-18.970519	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	2000	47.240234	-20.563613	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	2000	48.678221	-14.48446	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	2000	46.567827	-19.523708	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	2000	47.04425	-20.463767	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	2000	47.17095	-20.577924	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	2000	46.671481	-20.297712	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	2000	48.611646	-14.025755	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	2000	46.836639	-19.018703	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	2000	46.407548	-19.30419	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Fleas	2000	47.502774	-18.916144	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague

Fleas	2000	47.529835	-18.894468	Vogler AJ, Chan F, Wagner DM, Roumagnac P, Lee J, Nera R, et al. Phylogeography and Molecular Epidemiology of <i>Yersinia pestis</i> in Madagascar. PLoS neglected tropical diseases. 2011;5(9):e1319. Epub 2011/09/21. pmid:21931876;.
Rat	2000	47.50947	-18.904924	Vogler AJ, Chan F, Wagner DM, Roumagnac P, Lee J, Nera R, et al. Phylogeography and Molecular Epidemiology of <i>Yersinia pestis</i> in Madagascar. PLoS neglected tropical diseases. 2011;5(9):e1319. Epub 2011/09/21. pmid:21931876;.
Human	2000	48.375195	-18.887572	Temporal phylogeography of <i>Yersinia pestis</i> in Madagascar: Insights into the long-term maintenance of plague
Human	2000	48.993059	-14.6579	Vogler AJ, Chan F, Wagner DM, Roumagnac P, Lee J, et al. (2011) Phylogeography and Molecular Epidemiology of <i>Yersinia pestis</i> in Madagascar. PLoS Negl Trop Dis 5: e1319. pmid:21931876
Human	2000	47.410979	-20.395622	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1999	47.320332	-21.167362	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1999	46.803629	-20.551351	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1999	48.659697	-14.671503	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1999	47.617064	-18.951933	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1999	47.009097	-20.862028	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1999	46.863252	-20.962218	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1999	47.705096	-18.910731	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1999	47.254293	-18.488166	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1999	47.810334	-18.868182	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1999	47.109411	-20.962693	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1999	46.943931	-18.992048	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1999	47.216571	-21.666737	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1999	48.240884	-19.099538	Temporal phylogeography of <i>Yersinia pestis</i> in Madagascar: Insights into the long-term maintenance of plague
Human	1999	48.139707	-18.791602	Temporal phylogeography of <i>Yersinia pestis</i> in Madagascar: Insights into the long-term maintenance of plague
Human	1999	47.957998	-19.089277	Temporal phylogeography of <i>Yersinia pestis</i> in Madagascar: Insights into the long-term maintenance of plague
Human	1999	49.177119	-17.708612	Temporal phylogeography of <i>Yersinia pestis</i> in Madagascar: Insights into the long-term maintenance of plague

Human	1999	48.336497	-19.847175	Temporal phylogeography of <i>Yersinia pestis</i> in Madagascar: Insights into the long-term maintenance of plague
Human	1999	47.187568	-20.682861	Temporal phylogeography of <i>Yersinia pestis</i> in Madagascar: Insights into the long-term maintenance of plague
Human	1999	46.520834	-19.170172	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1999	47.015158	-18.991831	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1999	47.436731	-21.87993	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1998	47.691557	-18.988468	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1998	47.182811	-20.742476	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1998	46.910724	-20.269362	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1998	46.947736	-20.892463	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1998	46.888875	-21.181099	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1998	47.019651	-19.095774	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1998	46.917772	-21.390373	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1998	46.685721	-19.768214	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1998	46.739394	-19.168793	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1998	47.056765	-18.85341	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1998	47.103222	-20.848899	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1997	47.017837	-20.574931	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1997	47.184028	-20.55999	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1997	47.87991	-18.20544	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1997	47.015056	-21.140993	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1997	46.288366	-19.581991	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1997	47.73397	-22.019383	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1997	46.589401	-19.183433	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1997	47.837987	-19.137954	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1996	47.412107	-19.687913	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1996	47.297905	-21.662868	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague

Human	1996	47.179235	-19.017968	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1996	46.909387	-18.349644	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1996	46.931765	-21.7202	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1996	48.398358	-18.482302	Temporal phylogeography of <i>Yersinia pestis</i> in Madagascar: Insights into the long-term maintenance of plague
Human	1996	47.281369	-21.202988	Temporal phylogeography of <i>Yersinia pestis</i> in Madagascar: Insights into the long-term maintenance of plague
Human	1996	46.702035	-18.370865	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1995	47.069037	-20.343332	Vogler AJ, Chan F, Wagner DM, Roumagnac P, Lee J, Nera R, et al. Phylogeography and Molecular Epidemiology of <i>Yersinia pestis</i> in Madagascar. PLoS neglected tropical diseases. 2011;5(9):e1319. Epub 2011/09/21. pmid:21931876;.
Human	1995	46.774176	-21.909238	Vogler AJ, Chan F, Wagner DM, Roumagnac P, Lee J, Nera R, et al. Phylogeography and Molecular Epidemiology of <i>Yersinia pestis</i> in Madagascar. PLoS neglected tropical diseases. 2011;5(9):e1319. Epub 2011/09/21. pmid:21931876;.
Human	1994	48.288546	-20.393528	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Rat	1994	47.538758	-18.916199	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1992	48.259626	-18.388765	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1992	47.43533	-18.928385	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1989	47.356831	-20.250136	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1988	47.583142	-19.79412	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1987	49.55853	-14.616249	(2022). Transmission of antimicrobial resistant <i>Yersinia pestis</i> during a pneumonic plague outbreak. Clinical Infectious Diseases, 74(4), 695-702.
Human	1983	47.077627	-20.777692	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1979	47.234202	-19.902899	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1977	47.041178	-18.809479	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1976	46.732975	-19.040164	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1976	48.744916	-14.540582	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1975	46.899258	-21.635045	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1970	46.364333	-19.124253	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Rat	1962	48.229233	-18.947976	Guiyoule, A., Rasoamanana, B., Buchrieser, C., Michel, P., Chanteau, S., & Carniel, E. (1997). Recent emergence

				of new variants of <i>Yersinia pestis</i> in Madagascar. <i>Journal of Clinical Microbiology</i> , 35(11), 2826-2833.
Guinea Pig	1953	47.519388	-18.900359	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1946	46.86268	-18.880924	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1940	47.244801	-20.532748	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	1939	47.537284	-18.912275	A Decade of Plague in Mahajanga, Madagascar: Insights into the Global Maritime Spread of Pandemic Plague
Human	2017	46.83	-18.95	Multiple Introductions of <i>Yersinia pestis</i> during Urban Pneumonic Plague Epidemic, Madagascar, 2017” (Vol. 30, No. 2, 2024).
Human	2017	47.18	-20.283	Multiple Introductions of <i>Yersinia pestis</i> during Urban Pneumonic Plague Epidemic, Madagascar, 2017” (Vol. 30, No. 2, 2024).
Human	2017	47.351	-19.027	Multiple Introductions of <i>Yersinia pestis</i> during Urban Pneumonic Plague Epidemic, Madagascar, 2017” (Vol. 30, No. 2, 2024).
Human	2017	46.28	-18.88	Multiple Introductions of <i>Yersinia pestis</i> during Urban Pneumonic Plague Epidemic, Madagascar, 2017” (Vol. 30, No. 2, 2024).
Human	2017	46.1	-18.86	Multiple Introductions of <i>Yersinia pestis</i> during Urban Pneumonic Plague Epidemic, Madagascar, 2017” (Vol. 30, No. 2, 2024).
Human	2017	46.83	-18.95	Multiple Introductions of <i>Yersinia pestis</i> during Urban Pneumonic Plague Epidemic, Madagascar, 2017” (Vol. 30, No. 2, 2024).
Human	2017	47.18	-20.283	Multiple Introductions of <i>Yersinia pestis</i> during Urban Pneumonic Plague Epidemic, Madagascar, 2017” (Vol. 30, No. 2, 2024).
Human	2017	47.6	-18.85	Multiple Introductions of <i>Yersinia pestis</i> during Urban Pneumonic Plague Epidemic, Madagascar, 2017” (Vol. 30, No. 2, 2024).
Human	2017	46.95	-21.85	Multiple Introductions of <i>Yersinia pestis</i> during Urban Pneumonic Plague Epidemic, Madagascar, 2017” (Vol. 30, No. 2, 2024).

**Supplementary Table S3. GBIF Occurrence Citations Table**

Source	Year	Species	Occurrence ID	URL	Download Date
GBIF occurrence dataset	n.d.	<i>Ctenocephalide s felis</i>	732532391	<a href="https://www.gbif.org/occurrence/732532391">https://www.gbif.org/occurrence/732532391</a>	2026-02-26
GBIF occurrence dataset	2024	<i>Eliurus tanala</i>	5203215337	<a href="https://www.gbif.org/occurrence/5203215337">https://www.gbif.org/occurrence/5203215337</a>	2026-02-26

GBIF occurrence dataset	2008	<i>Eliurus tanala</i>	2521445869	<a href="https://www.gbif.org/occurrence/2521445869">https://www.gbif.org/occurrence/2521445869</a>	2026-02-26
GBIF occurrence dataset	2007	<i>Eliurus tanala</i>	2521440095	<a href="https://www.gbif.org/occurrence/2521440095">https://www.gbif.org/occurrence/2521440095</a>	2026-02-26
NMNH Material Samples (USNM)	1990	<i>Eliurus tanala</i>	3027979104	<a href="https://www.gbif.org/occurrence/3027979104">https://www.gbif.org/occurrence/3027979104</a>	2026-02-26
NMNH Material Samples (USNM)	1990	<i>Eliurus tanala</i>	3027980845	<a href="https://www.gbif.org/occurrence/3027980845">https://www.gbif.org/occurrence/3027980845</a>	2026-02-26
GBIF occurrence dataset	2024	<i>Eliurus webbi</i>	5203204460	<a href="https://www.gbif.org/occurrence/5203204460">https://www.gbif.org/occurrence/5203204460</a>	2026-02-26
GBIF occurrence dataset	2024	<i>Eliurus webbi</i>	5203211495	<a href="https://www.gbif.org/occurrence/5203211495">https://www.gbif.org/occurrence/5203211495</a>	2026-02-26
GBIF occurrence dataset	2024	<i>Eliurus webbi</i>	5203217316	<a href="https://www.gbif.org/occurrence/5203217316">https://www.gbif.org/occurrence/5203217316</a>	2026-02-26
NMNH Material Samples (USNM)	1990	<i>Eliurus webbi</i>	3027972683	<a href="https://www.gbif.org/occurrence/3027972683">https://www.gbif.org/occurrence/3027972683</a>	2026-02-26
NMNH Material Samples (USNM)	1990	<i>Eliurus webbi</i>	3027980118	<a href="https://www.gbif.org/occurrence/3027980118">https://www.gbif.org/occurrence/3027980118</a>	2026-02-26
GBIF occurrence dataset	2023	<i>Microgale brevicaudata</i>	5203205338	<a href="https://www.gbif.org/occurrence/5203205338">https://www.gbif.org/occurrence/5203205338</a>	2026-02-26
GBIF occurrence dataset	2023	<i>Microgale brevicaudata</i>	5203207320	<a href="https://www.gbif.org/occurrence/5203207320">https://www.gbif.org/occurrence/5203207320</a>	2026-02-26

GBIF occurrence dataset	2023	<i>Microgale brevicaudata</i>	5203209411	<a href="https://www.gbif.org/occurrence/520320941">https://www.gbif.org/occurrence/520320941</a>	2026-02-26
GBIF occurrence dataset	2023	<i>Mus musculus</i>	5203209443	<a href="https://www.gbif.org/occurrence/520320944">https://www.gbif.org/occurrence/520320944</a>	2026-02-26
GBIF occurrence dataset	2023	<i>Mus musculus</i>	5203204346	<a href="https://www.gbif.org/occurrence/520320434">https://www.gbif.org/occurrence/520320434</a>	2026-02-26
GBIF occurrence dataset	2023	<i>Mus musculus</i>	5203205421	<a href="https://www.gbif.org/occurrence/520320542">https://www.gbif.org/occurrence/520320542</a>	2026-02-26
iNaturalist research-grade observations	2016	<i>Mus musculus</i>	1901090599	<a href="https://www.gbif.org/occurrence/190109059">https://www.gbif.org/occurrence/190109059</a>	2026-02-26
ANWC salvage pre-Nagoya (12/10/2014)	2005	<i>Mus musculus</i>	2874243306	<a href="https://www.gbif.org/occurrence/287424330">https://www.gbif.org/occurrence/287424330</a>	2026-02-26
GBIF occurrence dataset	2008	<i>Nesogale talazaci</i>	5147112514	<a href="https://www.gbif.org/occurrence/514711251">https://www.gbif.org/occurrence/514711251</a>	2026-02-26
GBIF occurrence dataset	2006	<i>Nesogale talazaci</i>	5147113344	<a href="https://www.gbif.org/occurrence/514711334">https://www.gbif.org/occurrence/514711334</a>	2026-02-26
GBIF occurrence dataset	2006	<i>Nesogale talazaci</i>	5147224336	<a href="https://www.gbif.org/occurrence/514722433">https://www.gbif.org/occurrence/514722433</a>	2026-02-26
iNaturalist research-grade observations	2016	<i>Nesogale talazaci</i>	2460025910	<a href="https://www.gbif.org/occurrence/246002591">https://www.gbif.org/occurrence/246002591</a>	2026-02-26
iNaturalist research-grade observations	2016	<i>Nesogale talazaci</i>	5938171667	<a href="https://www.gbif.org/occurrence/593817166">https://www.gbif.org/occurrence/593817166</a>	2026-02-26

GBIF occurrence dataset	2010	<i>Nesomys rufus</i>	2521449680	<a href="https://www.gbif.org/occurrence/2521449680">https://www.gbif.org/occurrence/2521449680</a>	2026-02-26
GBIF occurrence dataset	2010	<i>Nesomys rufus</i>	2521450652	<a href="https://www.gbif.org/occurrence/2521450652">https://www.gbif.org/occurrence/2521450652</a>	2026-02-26
GBIF occurrence dataset	2008	<i>Nesomys rufus</i>	2521443787	<a href="https://www.gbif.org/occurrence/2521443787">https://www.gbif.org/occurrence/2521443787</a>	2026-02-26
NMNH Material Samples (USNM)	1988	<i>Nesomys rufus</i>	3027961593	<a href="https://www.gbif.org/occurrence/3027961593">https://www.gbif.org/occurrence/3027961593</a>	2026-02-26
NMNH Material Samples (USNM)	1988	<i>Nesomys rufus</i>	3027961725	<a href="https://www.gbif.org/occurrence/3027961725">https://www.gbif.org/occurrence/3027961725</a>	2026-02-26
GBIF occurrence dataset	2014	<i>Pulex irritans</i>	3350974094	<a href="https://www.gbif.org/occurrence/3350974094">https://www.gbif.org/occurrence/3350974094</a>	2026-02-26
GBIF occurrence dataset	2014	<i>Pulex irritans</i>	3350985819	<a href="https://www.gbif.org/occurrence/3350985819">https://www.gbif.org/occurrence/3350985819</a>	2026-02-26
GBIF occurrence dataset	2014	<i>Pulex irritans</i>	3350994934	<a href="https://www.gbif.org/occurrence/3350994934">https://www.gbif.org/occurrence/3350994934</a>	2026-02-26
GBIF occurrence dataset	1995	<i>Rattus norvegicus</i>	2521442671	<a href="https://www.gbif.org/occurrence/2521442671">https://www.gbif.org/occurrence/2521442671</a>	2026-02-26
GBIF occurrence dataset	2024	<i>Rattus rattus</i>	5203212329	<a href="https://www.gbif.org/occurrence/5203212329">https://www.gbif.org/occurrence/5203212329</a>	2026-02-26
GBIF occurrence dataset	2024	<i>Rattus rattus</i>	5203219308	<a href="https://www.gbif.org/occurrence/5203219308">https://www.gbif.org/occurrence/5203219308</a>	2026-02-26
GBIF occurrence dataset	2024	<i>Rattus rattus</i>	5203224515	<a href="https://www.gbif.org/occurrence/5203224515">https://www.gbif.org/occurrence/5203224515</a>	2026-02-26

NMNH Extant Biology	199 0	<i>Rattus rattus</i>	132106559 5	<a href="https://www.gbif.org/occurrence/132106559">https://www.gbif.org/occurrence/132106559</a> 5	2026-02- 26
NMNH Extant Biology	198 9	<i>Rattus rattus</i>	132033589 6	<a href="https://www.gbif.org/occurrence/132033589">https://www.gbif.org/occurrence/132033589</a> 6	2026-02- 26
GBIF occurrence dataset	202 3	<i>Setifer setosus</i>	520321040 3	<a href="https://www.gbif.org/occurrence/520321040">https://www.gbif.org/occurrence/520321040</a> 3	2026-02- 26
GBIF occurrence dataset	202 3	<i>Setifer setosus</i>	520322339 6	<a href="https://www.gbif.org/occurrence/520322339">https://www.gbif.org/occurrence/520322339</a> 6	2026-02- 26
GBIF occurrence dataset	202 3	<i>Setifer setosus</i>	520320730 2	<a href="https://www.gbif.org/occurrence/520320730">https://www.gbif.org/occurrence/520320730</a> 2	2026-02- 26
iNaturalist research- grade observations	202 6	<i>Setifer setosus</i>	613034246 7	<a href="https://www.gbif.org/occurrence/613034246">https://www.gbif.org/occurrence/613034246</a> 7	2026-02- 26
iNaturalist research- grade observations	202 5	<i>Setifer setosus</i>	576097877 6	<a href="https://www.gbif.org/occurrence/576097877">https://www.gbif.org/occurrence/576097877</a> 6	2026-02- 26
GBIF occurrence dataset	202 3	<i>Suncus murinus</i>	520321041 8	<a href="https://www.gbif.org/occurrence/520321041">https://www.gbif.org/occurrence/520321041</a> 8	2026-02- 26
GBIF occurrence dataset	202 3	<i>Suncus murinus</i>	520321340 5	<a href="https://www.gbif.org/occurrence/520321340">https://www.gbif.org/occurrence/520321340</a> 5	2026-02- 26
GBIF occurrence dataset	202 3	<i>Suncus murinus</i>	520322133 2	<a href="https://www.gbif.org/occurrence/520322133">https://www.gbif.org/occurrence/520322133</a> 2	2026-02- 26
Royal Belgian Institute of Natural Sciences Collection	197 2	<i>Suncus murinus</i>	302559538 6	<a href="https://www.gbif.org/occurrence/302559538">https://www.gbif.org/occurrence/302559538</a> 6	2026-02- 26

Royal Belgian Institute of Natural Sciences Collection	1972	<i>Suncus murinus</i>	3025643919	<a href="https://www.gbif.org/occurrence/3025643919">https://www.gbif.org/occurrence/3025643919</a>	2026-02-26
GBIF occurrence dataset	1960	<i>Synopsyllus fonquernii</i>	5196172452	<a href="https://www.gbif.org/occurrence/5196172452">https://www.gbif.org/occurrence/5196172452</a>	2026-02-26
GBIF occurrence dataset	1954	<i>Synopsyllus fonquernii</i>	5196172449	<a href="https://www.gbif.org/occurrence/5196172449">https://www.gbif.org/occurrence/5196172449</a>	2026-02-26
GBIF occurrence dataset	1952	<i>Synopsyllus fonquernii</i>	5196172500	<a href="https://www.gbif.org/occurrence/5196172500">https://www.gbif.org/occurrence/5196172500</a>	2026-02-26
GBIF occurrence dataset	2024	<i>Tenrec ecaudatus</i>	5203211368	<a href="https://www.gbif.org/occurrence/5203211368">https://www.gbif.org/occurrence/5203211368</a>	2026-02-26
GBIF occurrence dataset	2023	<i>Tenrec ecaudatus</i>	5203213359	<a href="https://www.gbif.org/occurrence/5203213359">https://www.gbif.org/occurrence/5203213359</a>	2026-02-26
GBIF occurrence dataset	2023	<i>Tenrec ecaudatus</i>	5203209327	<a href="https://www.gbif.org/occurrence/5203209327">https://www.gbif.org/occurrence/5203209327</a>	2026-02-26
iNaturalist research-grade observations	2025	<i>Tenrec ecaudatus</i>	5889453514	<a href="https://www.gbif.org/occurrence/5889453514">https://www.gbif.org/occurrence/5889453514</a>	2026-02-26
iNaturalist research-grade observations	2025	<i>Tenrec ecaudatus</i>	5932273579	<a href="https://www.gbif.org/occurrence/5932273579">https://www.gbif.org/occurrence/5932273579</a>	2026-02-26
GBIF occurrence dataset	2014	<i>Xenopsylla brasiliensis</i>	3348104814	<a href="https://www.gbif.org/occurrence/3348104814">https://www.gbif.org/occurrence/3348104814</a>	2026-02-26
GBIF occurrence dataset	2014	<i>Xenopsylla brasiliensis</i>	3348150654	<a href="https://www.gbif.org/occurrence/3348150654">https://www.gbif.org/occurrence/3348150654</a>	2026-02-26

GBIF occurrence dataset	2014	<i>Xenopsylla brasiliensis</i>	3348168855	<a href="https://www.gbif.org/occurrence/3348168855">https://www.gbif.org/occurrence/3348168855</a>	2026-02-26
GBIF occurrence dataset	2014	<i>Xenopsylla cheopis</i>	3348129068	<a href="https://www.gbif.org/occurrence/3348129068">https://www.gbif.org/occurrence/3348129068</a>	2026-02-26
GBIF occurrence dataset	2014	<i>Xenopsylla cheopis</i>	3348136627	<a href="https://www.gbif.org/occurrence/3348136627">https://www.gbif.org/occurrence/3348136627</a>	2026-02-26
GBIF occurrence dataset	2014	<i>Xenopsylla cheopis</i>	3348190603	<a href="https://www.gbif.org/occurrence/3348190603">https://www.gbif.org/occurrence/3348190603</a>	2026-02-26
NMNH Extant Biology	1948	<i>Xenopsylla cheopis</i>	2900405753	<a href="https://www.gbif.org/occurrence/2900405753">https://www.gbif.org/occurrence/2900405753</a>	2026-02-26

Supplementary Code S1. Spatial Downscaling and Population Risk Exposure Analysis

```
# =====
# Plague (Yersinia pestis) risk mapping – Madagascar
#
# ENM downscaling and population exposure analysis
#
# Part 1: Spatial downscaling of ENM to target resolution
# Part 2: Risk classification (ENM × population, 0–9)
# =====

setwd()
library(terra)
library(classInt)

# --- Configuration -----

enm_coarse_path <- ""
pop_path <- ""
boundary_path <- ""
out_dir <- ""

resample_method <- "bilinear"
clip_enm_values <- TRUE

ok_ckm <- requireNamespace("Ckmeans.1d.dp", quietly = TRUE)
dir.create(out_dir, recursive = TRUE, showWarnings = FALSE)

gdal_opts <- c("COMPRESS=LZW", "TILED=YES")
```

```

# --- Helper functions -----

sample_values <- function(r, n = 200000, seed = 42) {
  set.seed(seed)
  smp <- spatSample(r, size = min(n, ncell(r)), method = "regular",
    as.points = FALSE, values = TRUE, na.rm = TRUE)
  v <- as.numeric(if (is.data.frame(smp)) smp[, 1] else smp)
  v[is.finite(v)]
}

breaks_4 <- function(v) {
  if (ok_ckm) {
    ck <- Ckmeans.1d.dp::Ckmeans.1d.dp(v, k = 4)
    c(min(v), sapply(1:3, \i) max(v[ck$cluster == i])), max(v))
  } else {
    ci <- classIntervals(v, n = 4, style = "fisher")
    br <- ci$brks
    if (length(unique(br)) < 5) {
      c(min(v), quantile(v, c(.25, .50, .75)), max(v))
    } else br
  }
}

classify_4class <- function(r, br) {
  rc <- matrix(c(-Inf, br[2], 0,
    br[2], br[3], 1,
    br[3], br[4], 2,
    br[4], Inf, 3), ncol = 3, byrow = TRUE)
  out <- classify(r, rc, include.lowest = TRUE, right = TRUE)
  levels(out) <- NULL
  round(out)
}

# =====
# PART 1: Spatial downscaling
# =====

cat("--- Part 1: Spatial downscaling ---\n")

enm_coarse <- rast(enm_coarse_path)
pop <- rast(pop_path)
boundary <- vect(boundary_path)

if (crs(enm_coarse) != crs(pop)) {
  enm_coarse <- project(enm_coarse, pop, method = resample_method)
}

enm_coarse <- crop(enm_coarse, boundary)
pop <- crop(pop, boundary)

enm_fine <- resample(enm_coarse, pop, method = resample_method)

if (clip_enm_values) {
  enm_fine <- clamp(enm_fine,
    lower = global(enm_coarse, "min", na.rm = TRUE)[[1]],
    upper = global(enm_coarse, "max", na.rm = TRUE)[[1]])
}

```

```

}

enm_fine <- mask(enm_fine, boundary)
pop     <- mask(pop, boundary)

f_enm <- file.path(out_dir, "ENM_downscaled_100m.tif")
writeRaster(enm_fine, f_enm, overwrite = TRUE, gdal = gdal_opts)
cat(" Written:", f_enm, "\n")

# =====
# PART 2: Risk classification (ENM class × population class, 0–9)
# =====

cat("--- Part 2: Risk classification ---\n")

pop_cls <- classify_4class(pop, exp(breaks_4(log1p(sample_values(pop)))) - 1)
enm_cls <- classify_4class(enm_fine, breaks_4(sample_values(enm_fine, n = 100000)))

risk <- enm_cls * pop_cls
risk <- ifel(is.na(pop) | pop == 0, 0, risk)

f_pop_cls <- file.path(out_dir, "POP_class_0to3.tif")
f_enm_cls <- file.path(out_dir, "ENM_class_0to3.tif")
f_risk    <- file.path(out_dir, "RISK_0to9.tif")

writeRaster(pop_cls, f_pop_cls, overwrite = TRUE, datatype = "INT1U", gdal = gdal_opts)
writeRaster(enm_cls, f_enm_cls, overwrite = TRUE, datatype = "INT1U", gdal = gdal_opts)
writeRaster(risk, f_risk, overwrite = TRUE, datatype = "INT1U", gdal = gdal_opts)
cat(" Written:", f_pop_cls, "\n")
cat(" Written:", f_enm_cls, "\n")
cat(" Written:", f_risk, "\n")

# =====
# Zonal summary
# =====

cat("--- Zonal summary ---\n")

total_pop <- as.numeric(global(pop, "sum", na.rm = TRUE))

z <- as.data.frame(terra::zonal(pop, risk, fun = sum, na.rm = TRUE))
names(z) <- c("risk_class", "population")
z$risk_class <- as.integer(round(z$risk_class))
z$population <- round(z$population)
z$share     <- z$population / total_pop
z <- z[order(z$risk_class), ]

write.csv(z, file.path(out_dir, "people_by_risk_class1.csv"), row.names = FALSE)

cat("\n=== Summary ===\n")
cat("Total population: ", format(total_pop, big.mark = ","), "\n")
cat("Output directory: ", out_dir, "\n")
cat("Done.\n")

```

## Supplementary Code S2. Getis-Ord Gi\* hotspot analysis

```
# =====  
# Getis-Ord Gi* hotspot analysis of plague risk at fokontany (Admin 4) level  
# Input: RISK_0to9.tif (discrete values: 0,1,2,3,4,6,9)  
# =====  
  
setwd()  
library(terra)  
library(sf)  
library(spdep)  
library(dplyr)  
  
# --- Configuration -----  
  
risk_path <- ""  
pop_path <- ""  
fkt_path <- ""  
out_dir <- ""  
dist_threshold <- # metres  
  
# --- Load data -----  
  
cat("Loading data...\n")  
risk <- rast(risk_path)  
pop <- rast(pop_path)  
  
if (!compareGeom(risk, pop, stopOnError = FALSE)) {  
  cat(" Aligning pop to risk grid...\n")  
  pop <- resample(pop, risk, method = "bilinear")  
}  
  
stk <- c(risk, pop)  
names(stk) <- c("risk", "pop")  
  
fkt <- st_read(fkt_path, quiet = TRUE)  
fkt <- st_make_valid(fkt)  
fkt <- st_transform(fkt, 32738)  
  
cat(" Fokontany units:", nrow(fkt), "\n")  
  
# --- Zonal extraction -----  
  
cat("Extracting zonal statistics...\n")  
  
fkt$ZONE_ID <- seq_len(nrow(fkt))  
  
vals <- extract(stk, vect(st_transform(fkt, crs(risk))), na.rm = FALSE)  
vals <- as.data.frame(vals)  
names(vals) <- c("ZONE_ID", "risk", "pop")  
  
vals <- vals[!is.na(vals$risk) & !is.na(vals$pop), ]  
vals$pop[vals$pop < 0] <- 0  
vals$risk <- as.numeric(vals$risk)  
vals$pop <- as.numeric(vals$pop)
```

```

# --- Aggregate to fokontany -----

mean_risk <- vals %>%
  group_by(ZONE_ID) %>%
  summarise(
    mean_risk = mean(risk, na.rm = TRUE),
    max_risk = max(risk, na.rm = TRUE),
    total_pop = sum(pop, na.rm = TRUE),
    n_pixels = n(),
    .groups = "drop"
  )

weighted <- vals %>%
  filter(pop > 0) %>%
  group_by(ZONE_ID) %>%
  summarise(
    weighted_risk = sum(risk * pop, na.rm = TRUE) / sum(pop, na.rm = TRUE),
    .groups = "drop"
  )

fkt <- left_join(fkt, mean_risk, by = "ZONE_ID")
fkt <- left_join(fkt, weighted, by = "ZONE_ID")

fkt$mean_risk[is.na(fkt$mean_risk)] <- 0
fkt$max_risk[is.na(fkt$max_risk)] <- 0
fkt$total_pop[is.na(fkt$total_pop)] <- 0
fkt$weighted_risk[is.na(fkt$weighted_risk)] <- 0

fkt$mean_risk <- as.numeric(fkt$mean_risk)
fkt$weighted_risk <- as.numeric(fkt$weighted_risk)
fkt$total_pop <- as.numeric(fkt$total_pop)

fkt_analysis <- fkt[fkt$n_pixels > 0 & fkt$total_pop > 0, ]
cat(" Fokontany with data:", nrow(fkt_analysis), "\n")

# --- Spatial weights -----

cat("Building spatial weights (", dist_threshold / 1000, "km threshold)... \n")

coords <- st_coordinates(st_centroid(fkt_analysis))
nb <- dnearneigh(coords, d1 = 0, d2 = dist_threshold)

n_isolates <- sum(card(nb) == 0)
cat(" Isolates:", n_isolates, "of", nrow(fkt_analysis), "\n")

if (n_isolates > 0) {
  cat(" Removing", n_isolates, "isolates from analysis\n")
  fkt_analysis <- fkt_analysis[-which(card(nb) == 0), ]
  coords <- st_coordinates(st_centroid(fkt_analysis))
  nb <- dnearneigh(coords, d1 = 0, d2 = dist_threshold)
}

lw <- nb2listw(nb, style = "W", zero.policy = TRUE)

cat(" Mean neighbours per unit:", round(mean(card(nb)), 1), "\n")

```

```

# --- Global spatial autocorrelation -----

cat("Testing global spatial autocorrelation...\n")
moran_result <- moran.test(fkt_analysis$weighted_risk, lw, zero.policy = TRUE)
cat(" Moran's I:", round(moran_result$estimate[1], 4),
    " p-value:", format.pval(moran_result$p.value), "\n")

if (moran_result$p.value > 0.05) {
  warning("No significant global spatial autocorrelation detected.
    Local Gi* results should be interpreted with caution.")
}

# --- Getis-Ord Gi* -----

cat("Running Gi*...\n")

gi <- localG(fkt_analysis$weighted_risk, lw, zero.policy = TRUE)

fkt_analysis$gi_zscore <- as.numeric(gi)
fkt_analysis$gi_pvalue <- 2 * pnorm(-abs(fkt_analysis$gi_zscore))

fkt_analysis$cluster <- "Not significant"
fkt_analysis$cluster[fkt_analysis$gi_pvalue < 0.05 & fkt_analysis$gi_zscore > 0] <- "Hotspot"
fkt_analysis$cluster[fkt_analysis$gi_pvalue < 0.05 & fkt_analysis$gi_zscore < 0] <- "Coldspot"

fkt_analysis$confidence <- case_when(
  fkt_analysis$gi_pvalue >= 0.05 ~ "Not significant",
  fkt_analysis$gi_pvalue < 0.001 & fkt_analysis$gi_zscore > 0 ~ "Hot 99%",
  fkt_analysis$gi_pvalue < 0.01 & fkt_analysis$gi_zscore > 0 ~ "Hot 95%",
  fkt_analysis$gi_pvalue < 0.05 & fkt_analysis$gi_zscore > 0 ~ "Hot 90%",
  fkt_analysis$gi_pvalue < 0.001 & fkt_analysis$gi_zscore < 0 ~ "Cold 99%",
  fkt_analysis$gi_pvalue < 0.01 & fkt_analysis$gi_zscore < 0 ~ "Cold 95%",
  fkt_analysis$gi_pvalue < 0.05 & fkt_analysis$gi_zscore < 0 ~ "Cold 90%",
  TRUE ~ "Not significant"
)

# --- Summary -----

cat("\n=== Gi* Results ===\n")
cat("Cluster counts:\n")
print(table(fkt_analysis$cluster))
cat("\nConfidence breakdown:\n")
print(table(fkt_analysis$confidence))

hot <- fkt_analysis[fkt_analysis$cluster == "Hotspot", ]
cat("\nHotspot fokontany:", nrow(hot), "\n")
cat("Population in hotspots:", format(sum(hot$total_pop), big.mark = ","), "\n")
cat("Mean weighted risk in hotspots:", round(mean(hot$weighted_risk), 2), "\n")

# --- Export -----

# Force shapefile-compatible types
fkt_analysis$ZONE_ID <- as.integer(fkt_analysis$ZONE_ID)

```

```

fkt_analysis$n_pixels <- as.integer(fkt_analysis$n_pixels)
fkt_analysis$total_pop <- as.double(fkt_analysis$total_pop)
fkt_analysis$max_risk <- as.integer(fkt_analysis$max_risk)

# Rename for shapefile 10-character limit
fkt_analysis <- fkt_analysis %>%
  rename(w_risk = weighted_risk,
         m_risk = mean_risk,
         mx_risk = max_risk,
         tot_pop = total_pop,
         gi_z = gi_zscore,
         gi_p = gi_pvalue,
         conf = confidence)

st_write(fkt_analysis, file.path(out_dir, "fokontany_Gi_starnew1.shp"),
        delete_dsn = TRUE)

out_csv <- st_drop_geometry(fkt_analysis) %>%
  select(ZONE_ID, NAME_4, m_risk, w_risk, mx_risk, tot_pop,
        gi_z, gi_p, cluster, conf)

write.csv(out_csv, file.path(out_dir, "fokontany_Gi_starnew1.csv"),
        row.names = FALSE)

cat("\nOutputs saved to:", out_dir, "\n")
cat("Done.\n")

```