Biophysical and socioeconomic drivers of oil palm expansion in Indonesia

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Supplementary Information

S1. Spatial panel models

Our objective is to estimate the following model efficiently and consistently:

$$d_{it} = exp(\alpha + \beta X_{it} + \varepsilon_{it}), \quad (1)$$

where d_{it} is the area of oil palm expansion into each source land at regency *i* over year *t* – 1 and *t*. *X* is a panel of explanatory variables (time-variant and time-invariant; same as those listed in the pooled model) and ε_{it} is an error term.

$$log\ (d_{it}) = \alpha + \beta X_{it} + \varepsilon_{it} \quad (2)$$

For oil palm expansion models, the standard pooled estimation may be insufficient due to the individual heterogeneity and the spatial autocorrelation of land-use change among regencies. Therefore, spatial panel models, including spatially lagged dependent variable, spatial error autocorrelation, and spatial Durbin models, were implemented. We ran random effect rather than fixed effect regressions, because we are also interested in the time-invariant variables.

Random effect spatial lag models

$$log\ (d_{it}) = \lambda \sum_{j=1}^{N} w_{ij}\ log\ (d_{jt}) + X_{it}\boldsymbol{\beta} + \varepsilon_{it} \quad (3)$$

$$\varepsilon_{it} = a_i + u_{it} \quad (4)$$

$$E(u_t)=0;\ E(u_t u_t) = \sigma^2 I_N \quad (5)$$

Random effect spatial error models

$$log\ (d_{it}) = X_{it}\boldsymbol{\beta} + \varphi_{it} \quad (6)$$

$$\varphi_{it} = \rho \sum_{j=1}^{N} w_{ij}\ \varphi_{jt} + \alpha_i + u_{it} \quad (7)$$

$$\varepsilon_{it} = a_i + u_{it} \quad (8)$$

$$E(u_t)=0;\ E(u_t u_t) = \sigma^2 I_N \quad (9)$$

Random effect spatial Durbin models

$$log\ (d_{it}) = \lambda \sum_{j=1}^{N} w_{ij}\ log\ (d_{jt}) + \alpha_i + X_{it}\boldsymbol{\beta_1} + \rho \sum_{j=1}^{N} w_{ij}\ X_{it}\boldsymbol{\beta_2} + \varepsilon_{it} \quad (10)$$

$$\varepsilon_{it} = a_i + u_{it} \quad (11)$$

$$E(u_t)=0;\ E(u_t u_t) = \sigma^2 I_N \quad (12)$$

In Eqs. (3), (6), (15),

- d_{it} represents the aggregate indicator of water quality in year *t*.
- X_{it} includes 1) the time-variant variable: climatic factors in year *t*, such as annual precipitation, precipitation in the driest month, average annual temperature, shortwave radiation; the percentage of regency within a protected area in year t; population density in year t; source land ratio (second-order polynomial) in year t, and export value averaged over the previous period; and 2) Time-invariant variables: biophysical and geographical factors, such as potential yield of oil palm plantation, slope, elevation, AWC, peatland percentage; and factors characterizing accessibility to market and infrastructure, such as average access time large cities, density of palm oil mills, and percentage of estate crop plantation in 1990.
- w_{ij} is the spatial weight.

Table S1. Land use and Land cover classification

Class	Description	Re-Class
Primary Dryland Forest	Natural forest, dry habitat	Primary Forest
Secondary Dryland Forest	Logging signs, dry habitat	Secondary Forest
Primary Mangrove Forest	No or low human activity, wetland forest in coastal areas	Primary Forest
Secondary Mangrove Forest	Logging signs, wetland forest in coastal areas	Secondary Forest
Primary Swamp Forest	Natural forest, wet habitat	Primary Forest
Secondary Swamp Forest	Logging signs, wet habitat	Secondary Forest
Plantation Forest	Dominated by homogeneous tree species for specific purposes, structural composition. Reforestation, industrial plantation forest, community plantation forest	Others
Dry Shrub	Highly degraded logged-over area, non-wet habitat, ongoing process of succession	Shrub
Wet Shrub	Highly degraded logged-over area, wet habitat, ongoing process of succession	Shrub
Savanna and Grasses	Grasses and scattered natural trees and shrubs	Others
Pure Dry Agriculture	Agricultural activities on dry/ non-wet land, e.g. moor, mixed garden, agriculture fields	Dry Agriculture
Mixed Dry Agriculture	Agricultural activities on dry/ non-wet land mixed with shrubs, thickets, and logged-over forest	Dry Agriculture
Paddy Field	Agriculture areas on wet habitat, especially for paddy	Others
Estate Crop	Planted estate areas, mostly with perennials crops or other agricultural trees commodities	Estate Crop
Settlement Areas	Rural, urban, industrial and other built-up areas	Others
Transmigration Areas	Unique settlement areas associated with houses and agroforestry and/or garden	Others
Port and Harbor	Big enough to be delineated as independent object	Others
Bare Ground	No vegetation cover	Bare Ground
Mining Areas	Open mining activities	Others
Open Swamp	Wetland with few vegetation	Others
Fish Pond/Aquaculture	Aquaculture activities	Others
Open Water	Ocean, rivers, lakes, and ponds	Others
Cloud and No-Data	Clouds, cloud shadows or data gaps with a size of more than 4 cm^2 at 100,000 scale display	No Data (Removed)

Table S2. Variable, data description and data sources

Variable	Data Description	Data Source
Land cover and land use	Land use and land cover maps of Indonesia, 1990-2015	Indonesian Ministry of the Environment Life and Forestry. 2020. Indonesian Land Cover Closure. Available at: http://webgis.menlhk.go.id:8080/pl/pl.htm.
Potential yield of oil palm	IIASA/FAO. Global Agro-ecological Zones (GAEZ v3.0, v4)	http://webarchive.iiasa.ac.at/Research/LUC/GAEZv3.0/ https://iiasa.ac.at/web/home/research/researchPrograms/water/GAEZ_v.4_Data_Portal.html
Precipitation (Rainfall)	Weedon, G.P., G. Balsamo, N. Bellouin, S. Gomes, MJ Best, and P. Viterbo, 2014: The WFDEI meteorological forcing data set. WATCH Forcing Data methodology applied to ERA-Interim reanalysis data. Water Resource Research, 50: 7505-14.	https://doi.org/10.5065/486N-8109.
Precipitation of driest month		
Temperature		
Radiation (shortwave)		
Export quantity and value	Export quantity and value of palm oil and products, UN-FAO	http://www.fao.org/faostat/en/#data/TP.
Palm oil mill density	Universal Mill List (UML) (WRI/ Rainforest Alliance /Proforest/Daemeter, 2018)	www.globalforestwatch.org
Access time	Travel time to major cities: A global map of Accessibility (Nelson, A., 2008)	https://forobs.jrc.ec.europa.eu/products/gam/index.php
Elevation	Shuttle Radar Topography Mission (NASA, 2009)	https://earthexplorer.usgs.gov/
Slope		
Available Water Capacity (AWC)	Harmonized world soil database (HWSD) (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012)	http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/
Peatland percentage	Peat lands (World Resources Institute, 2012. Accessed through Global Forest Watch)	www.globalforestwatch.org
Population density	Gridded Population of the World (GPW) (CIESIN)	http://sedac.ciesin.columbia.edu/gpw/index.jsp http://dx.doi.org/10.7927/H4NP22DQ
Protected area	World Database on Protected Areas (WDPA). IUCN and UNEP. Cambridge (UK). c2014.	www.protectedplanet.net
Sub-national administrative boundary	GeoNetwork – Sub-national Administrative Units of Indonesia. (FAO, 2002)	http://www.fao.org/geonetwork/srv/en/main.home?uuid=c8ee1300-88fd-11da-a88f-000d939bc5d8

Table S3. Measurement units and summary statistics of variables

Variable	Unit	Indonesia			Sumatra			Kalimantan		
		mean	min	max	mean	min	max	mean	min	max
Expansion into forest	‰	1.17	0	185.94	3.33	0	146.90	2.78	0	185.94
Expansion into shrub	‰	1.12	0	257.86	2.81	0	257.86	3.40	0	57.50
Expansion into dry agriculture	‰	0.77	0	152.63	1.91	0	152.63	2.16	0	129.13
Potential yield of oil palm	ton/ha	49.03	0	75.91	57.48	5.62	72.15	65.74	43.26	71.16
Plantation in 1990	%	3.20	0	71.76	9.35	0	71.76	1.77	0	16.23
Precipitation	mm/day	6.96	2.80	13.41	7.67	4.21	12.42	7.87	5.30	12.75
Precipitation of driest month	mm/day	0.72	0	6.68	1.32	0	5.58	1.09	0	5.38
Temperature	K	299.53	296.51	301.45	299.76	296.76	301.29	299.81	298.12	301.14
Radiation	W/m^2	206.06	154.02	248.85	187.06	165.31	205.94	189.39	167.93	212.72
Export value	Billion 2000 USD	4.55	0.66	13.66	4.55	0.66	13.66	4.55	0.66	13.66
Palm oil mill density	$/100\ km^2$	0.041	0	3.35	0.16	0	3.35	0.028	0	0.39
Access time	day	0.28	1.48E-3	2.50	0.28	6.62E-3	0.97	0.67	0.035	2.067
Elevation	100m	3.02	0.026	14.66	3.66	0.050	14.66	1.52	0.065	5.55
Slope	degree	4.91	0.20	16.91	5.40	0.29	16.91	3.49	0.20	9.69
AWC	m/m	0.12	0.015	0.15	0.12	0.050	0.15	0.12	0.069	0.15
Peatland	%	3.00	0	73.22	6.50	0	62.98	10.84	0	73.22
Population density	k persons $/km^2$	0.85	1.74E-3	16.13	0.23	0.020	6.59	0.11	2.70E-3	2.07
Protected area	%	6.00	0	78.27	10.53	0	78.27	5.58	0	26.33
Forest ratio	1	0.24	0	0.98	0.29	0	0.81	0.41	0	0.93
Shrub ratio	1	0.090	0	0.97	0.10	0	0.73	0.18	1.16E-4	0.69
Dry agriculture ratio	1	0.28	0	0.97	0.36	0	0.94	0.27	8.88E-3	0.82

Table S4.1 Pairwise correlations between explanatory variables in country models

	Shortwave radiation	Precipitation	Driest month precipitation	Temp	Protected %	Elevation	Slope	Mill density	AWC	Access time	Population	Natural forest ratio	Shrub ratio	Dry agriculture	Oil palm potential	Export value (t-1)	Peatland %	Plantation in 1990
Shortwave radiation	1	-0.525	-0.55	-0.052	-0.243	-0.066	-0.033	-0.195	-0.19	-0.419	0.084	-0.374	-0.101	-0.043	-0.58	-0.047	-0.278	-0.219
Precipitation	-0.525	1	0.61	-0.041	0.251	0.117	0.002	0.044	0.189	0.291	-0.04	0.141	-0.039	0.089	0.454	0.06	0.156	0.089
Driest month precipitation	-0.55	0.61	1	-0.086	0.334	0.137	0.123	0.11	0.113	0.447	-0.073	0.354	0.002	0.007	0.273	0.075	0.179	0.197
Temp	-0.052	-0.041	-0.086	1	-0.318	-0.766	-0.763	0.175	0.026	-0.304	0.24	-0.458	-0.014	0.007	0.491	0.025	0.244	0.119
Protected %	-0.243	0.251	0.334	-0.318	1	0.397	0.392	-0.039	0.02	0.416	-0.192	0.547	0.023	-0.096	-0.115	0.002	0.074	-0.034
Elevation	-0.066	0.117	0.137	-0.766	0.397	1	0.787	-0.123	-0.089	0.215	-0.209	0.367	-0.077	-0.006	-0.488	0	-0.222	-0.077
Slope	-0.033	0.002	0.123	-0.763	0.392	0.787	1	-0.144	-0.159	0.29	-0.323	0.575	0.076	0.036	-0.407	0	-0.249	-0.118
Mill density	-0.195	0.044	0.11	0.175	-0.039	-0.123	-0.144	1	0.064	-0.041	-0.06	-0.07	-0.054	0.105	0.173	0	0.206	0.484
AWC	-0.19	0.189	0.113	0.026	0.02	-0.089	-0.159	0.064	1	0.008	0.149	-0.059	-0.167	0.003	0.27	0	0.122	0.105
Access time	-0.419	0.291	0.447	-0.304	0.416	0.215	0.29	-0.041	0.008	1	-0.257	0.743	0.17	-0.276	0.022	0	0.226	-0.094
Population	0.084	-0.04	-0.073	0.24	-0.192	-0.209	-0.323	-0.06	0.149	-0.257	1	-0.321	-0.136	-0.208	0.054	0.018	-0.116	-0.078
Natural forest ratio	-0.374	0.141	0.354	-0.458	0.547	0.367	0.575	-0.07	-0.059	0.743	-0.321	1	0.172	-0.304	-0.095	-0.05	0.136	-0.115
Shrub ratio	-0.101	-0.039	0.002	-0.014	0.023	-0.077	0.076	-0.054	-0.167	0.17	-0.136	0.172	1	-0.138	0.06	-0.069	0.173	-0.055
Dry agriculture ratio	-0.043	0.089	0.007	0.007	-0.096	-0.006	0.036	0.105	0.003	-0.276	-0.208	-0.304	-0.138	1	0.167	0.054	-0.072	0.073
Oil palm potential yield	-0.58	0.454	0.273	0.491	-0.115	-0.488	-0.407	0.173	0.27	0.022	0.054	-0.095	0.06	0.167	1	0.001	0.28	0.219
Export value (t-1)	-0.047	0.06	0.075	0.025	0.002	0	0	0	0	0	0.018	-0.05	-0.069	0.054	0.001	1	0	0
Peatland %	-0.278	0.156	0.179	0.244	0.074	-0.222	-0.249	0.206	0.122	0.226	-0.116	0.136	0.173	-0.072	0.28	0	1	0.133
Plantation in 1990	-0.219	0.089	0.197	0.119	-0.034	-0.077	-0.118	0.484	0.105	-0.094	-0.078	-0.115	-0.055	0.073	0.219	0	0.133	1

Table S4.2 Pairwise correlations between explanatory variables in Sumatra models

	Shortwave radiation	Precipitation	Driest month precipitation	Temp	Protected %	Elevation	Slope	Mill density	AWC	Access time	Population	Natural forest ratio	Shrub ratio	Dry agriculture	Oil palm potential	Export value (t-1)	Peatland %	Plantation in 1990
Shortwave radiation	1	-0.214	-0.314	-0.078	0.196	0.023	0.061	-0.242	0.221	0.001	0.093	0.049	-0.017	0.199	-0.101	-0.219	-0.182	-0.207
Precipitation	-0.214	1	0.603	-0.152	0.276	0.114	0.145	-0.082	0	0.092	-0.114	0.094	-0.049	0.058	-0.083	0.016	-0.166	-0.032
Driest month precipitation	-0.314	0.603	1	-0.096	0.203	0.09	0.111	0.028	-0.08	0.204	0.015	0.12	-0.117	-0.163	-0.077	0.135	-0.03	0.168
Temp	-0.078	-0.152	-0.096	1	-0.399	-0.903	-0.779	0.291	0.284	-0.364	0.141	-0.535	0.13	0.062	0.832	0.117	0.458	0.279
Protected %	0.196	0.276	0.203	-0.399	1	0.5	0.435	-0.148	0.016	0.516	-0.13	0.614	-0.155	-0.249	-0.527	0.004	-0.099	-0.226
Elevation	0.023	0.114	0.09	-0.903	0.5	1	0.837	-0.253	-0.334	0.408	-0.138	0.624	-0.117	-0.17	-0.893	0	-0.398	-0.327
Slope	0.061	0.145	0.111	-0.779	0.435	0.837	1	-0.288	-0.522	0.463	-0.179	0.731	-0.012	-0.246	-0.661	0	-0.436	-0.377
Mill density	-0.242	-0.082	0.028	0.291	-0.148	-0.253	-0.288	1	0.107	-0.191	-0.048	-0.259	-0.182	0.105	0.228	0	0.169	0.464
AWC	0.221	0	-0.08	0.284	0.016	-0.334	-0.522	0.107	1	-0.247	0.067	-0.27	-0.194	0.191	0.165	0	0.241	0.241
Access time	0.001	0.092	0.204	-0.364	0.516	0.408	0.463	-0.191	-0.247	1	-0.281	0.711	0.242	-0.524	-0.512	0	0.205	-0.335
Population	0.093	-0.114	0.015	0.141	-0.13	-0.138	-0.179	-0.048	0.067	-0.281	1	-0.245	-0.183	-0.11	0.152	0.014	-0.114	0.104
Natural forest ratio	0.049	0.094	0.12	-0.535	0.614	0.624	0.731	-0.259	-0.27	0.711	-0.245	1	-0.052	-0.551	-0.596	-0.104	-0.068	-0.403
Shrub ratio	-0.017	-0.049	-0.117	0.13	-0.155	-0.117	-0.012	-0.182	-0.194	0.242	-0.183	-0.052	1	-0.253	0.052	-0.065	0.198	-0.264
Dry agriculture ratio	0.199	0.058	-0.163	0.062	-0.249	-0.17	-0.246	0.105	0.191	-0.524	-0.11	-0.551	-0.253	1	0.228	0.046	-0.285	-0.041
Oil palm potential yield	-0.101	-0.083	-0.077	0.832	-0.527	-0.893	-0.661	0.228	0.165	-0.512	0.152	-0.596	0.052	0.228	1	0.007	0.299	0.309
Export value (t-1)	-0.219	0.016	0.135	0.117	0.004	0	0	0	0	0	0.014	-0.104	-0.065	0.046	0.007	1	0	0
Peatland %	-0.182	-0.166	-0.03	0.458	-0.099	-0.398	-0.436	0.169	0.241	0.205	-0.114	-0.068	0.198	-0.285	0.299	0	1	0.132
Plantation in 1990	-0.207	-0.032	0.168	0.279	-0.226	-0.327	-0.377	0.464	0.241	-0.335	0.104	-0.403	-0.264	-0.041	0.309	0	0.132	1

Table S4.3 Pairwise correlations between explanatory variables in Kalimantan models

	Shortwave radiation	Precipitation	Driest month precipitation	Temp	Protected %	Elevation	Slope	Mill density	AWC	Access time	Population	Natural forest ratio	Shrub ratio	Dry agriculture ratio	Oil palm potential yield	Export value (t-1)	Peatland %	Plantation in 1990
Shortwave radiation	1	-0.231	-0.315	0.485	-0.042	-0.445	-0.381	0.387	-0.269	-0.495	0.116	-0.557	-0.204	0.524	0.127	-0.156	0.287	0.039
Precipitation	-0.231	1	0.729	-0.287	0.257	0.107	0.079	0.118	0.333	0.518	-0.244	0.335	-0.174	-0.121	-0.16	0.127	0.177	-0.146
Driest month precipitation	-0.315	0.729	1	-0.36	0.154	0.31	0.241	0.073	0.435	0.528	-0.095	0.382	-0.198	-0.158	-0.363	0.206	0.028	-0.145
Temp	0.485	-0.287	-0.36	1	-0.274	-0.877	-0.818	0.319	-0.112	-0.631	0.472	-0.708	0.414	0.256	0.703	0.096	0.356	0.222
Protected %	-0.042	0.257	0.154	-0.274	1	0.18	0.164	-0.081	-0.021	0.555	-0.298	0.384	0.004	-0.42	-0.372	0	0.152	0.082
Elevation	-0.445	0.107	0.31	-0.877	0.18	1	0.964	-0.261	0.014	0.522	-0.312	0.698	-0.363	-0.294	-0.818	0	-0.384	-0.202
Slope	-0.381	0.079	0.241	-0.818	0.164	0.964	1	-0.269	-0.156	0.454	-0.298	0.633	-0.387	-0.224	-0.752	0	-0.47	-0.143
Mill density	0.387	0.118	0.073	0.319	-0.081	-0.261	-0.269	1	0.159	-0.166	0.09	-0.247	-0.226	0.292	0.101	0	0.607	0.106
AWC	-0.269	0.333	0.435	-0.112	-0.021	0.014	-0.156	0.159	1	0.289	0.142	0.174	0.012	-0.121	-0.11	0	0.231	-0.148
Access time	-0.495	0.518	0.528	-0.631	0.555	0.522	0.454	-0.166	0.289	1	-0.456	0.782	-0.154	-0.539	-0.466	0	-0.05	-0.172
Population	0.116	-0.244	-0.095	0.472	-0.298	-0.312	-0.298	0.09	0.142	-0.456	1	-0.47	0.303	0.217	0.214	0.075	-0.009	-0.173
Natural forest ratio	-0.557	0.335	0.382	-0.708	0.384	0.698	0.633	-0.247	0.174	0.782	-0.47	1	-0.181	-0.716	-0.479	-0.143	-0.12	-0.104
Shrub ratio	-0.204	-0.174	-0.198	0.414	0.004	-0.363	-0.387	-0.226	0.012	-0.154	0.303	-0.181	1	-0.482	0.366	-0.016	0.082	0.098
Dry agriculture ratio	0.524	-0.121	-0.158	0.256	-0.42	-0.294	-0.224	0.292	-0.121	-0.539	0.217	-0.716	-0.482	1	0.132	0.048	0.007	-0.087
Oil palm potential yield	0.127	-0.16	-0.363	0.703	-0.372	-0.818	-0.752	0.101	-0.11	-0.466	0.214	-0.479	0.366	0.132	1	0	0.143	0.267
Export value (t-1)	-0.156	0.127	0.206	0.096	0	0	0	0	0	0	0.075	-0.143	-0.016	0.048	0	1	0	0
Peatland %	0.287	0.177	0.028	0.356	0.152	-0.384	-0.47	0.607	0.231	-0.05	-0.009	-0.12	0.082	0.007	0.143	0	1	-0.145
Plantation in 1990	0.039	-0.146	-0.145	0.222	0.082	-0.202	-0.143	0.106	-0.148	-0.172	-0.173	-0.104	0.098	-0.087	0.267	0	-0.145	1

Table S5 Variance inflation factors

	Indonesia	Sumatra	Kalimantan
Shortwave radiation	3.23	1.945	3.764
Precipitation	2.338	2.085	3.581
Driest month precipitation	2.145	2.03	3.316
Temp	3.614	8.219	12.06
Protected %	1.672	2.481	3.489
Elevation	5.215	17.987	75.805
Slope	5.434	10.281	38.412
Mill density	1.392	1.55	2.962
AWC	1.233	2.082	2.649
Access time	2.865	3.934	5.598
Population	1.413	1.768	2.561
Natural forest ratio	5.283	9.281	28.235
Shrub ratio	1.226	2.339	10.016
Dry agriculture ratio	1.607	4.218	19.743
Oil palm potential yield	3.621	9.572	8.671
Export value (t-1)	1.034	1.395	1.95
Peatland %	1.388	2.256	3.784
Plantation in 1990	1.491	2.519	2.001

* Synthesizing the pairwise correlations and VIFs, we eliminated elevation from the Sumatra and Kalimantan models.

Table S6. Results of pooled and spatial panel models for bare ground expansion to natural forest in Kalimantan

	Pooled			Spatial Lag			Spatial Error			Spatial Durbin		
	$\hat{\beta}$	t-value	sig.	$\hat{\beta}$	t-value	sig.	$\hat{\beta}$	t-value	sig.	$\hat{\beta}$	t-value	sig.
(Intercept)	-780.084	-1.622		-584.550	-1.233		-813.448	-1.575		-706.839	-1.326	
Oil palm potential yield	0.027	0.203		0.014	0.104		0.061	0.480		0.071	0.598	
Plantation 1990	0.145	1.009		0.195	1.291		0.131	0.904		0.088	0.625	
Mill density	7.088	0.877		6.175	0.725		6.635	0.921		6.998	1.070	
Access time	1.879	1.290		1.374	0.917		1.235	0.825		1.000	0.680	
Temperature	2.542	1.567		1.908	1.195		2.633	1.515		2.252	1.257	
Shortwave radiation	0.041	0.719		0.036	0.620		0.067	1.119		0.089	1.438	
Precipitation	-0.125	-0.260		-0.136	-0.295		-0.082	-0.151		0.069	0.119	
Driest month precipitation	1.430	2.744	***	1.100	2.300	*	1.661	2.703	***	1.726	2.583	***
AWC	12.269	0.436		0.804	0.028		-7.747	-0.263		-10.109	-0.349	
Slope	-0.280	-0.615		-0.311	-0.666		-0.242	-0.537		-0.323	-0.742	
Source land ratio	9.009	1.194		7.841	1.072		10.535	1.498		9.638	1.468	
Source land ratio2	-6.907	-0.838		-6.065	-0.757		-6.116	-0.808		-4.311	-0.619	
Population density	-11.846	-4.543	****	-12.420	-4.764	****	-11.365	-4.365	****	-9.780	-3.771	
Export value	0.222	2.482	**	0.138	1.701	*	0.220	1.728	*	0.361	1.729	****
Peatland	-0.069	-1.908	*	-0.072	-1.915	*	-0.073	-2.027	**	-0.066	-1.861	*
Protected %	0.143	1.785	*	0.161	1.894	*	0.164	2.169	**	0.132	1.874	*
phi				6.71E-02	0.930		3.19E-02	0.672		3.55E-02	0.738	*
rho							0.441	5.997	****	0.707	8.610	****
lambda				0.368	4.852	****				-0.474	-2.940	***
R2	0.411											
AIC	1433.057			1480.652			1472.891			1468.827		
LogLik	-698.529			-688.326			-684.446			-681.414		

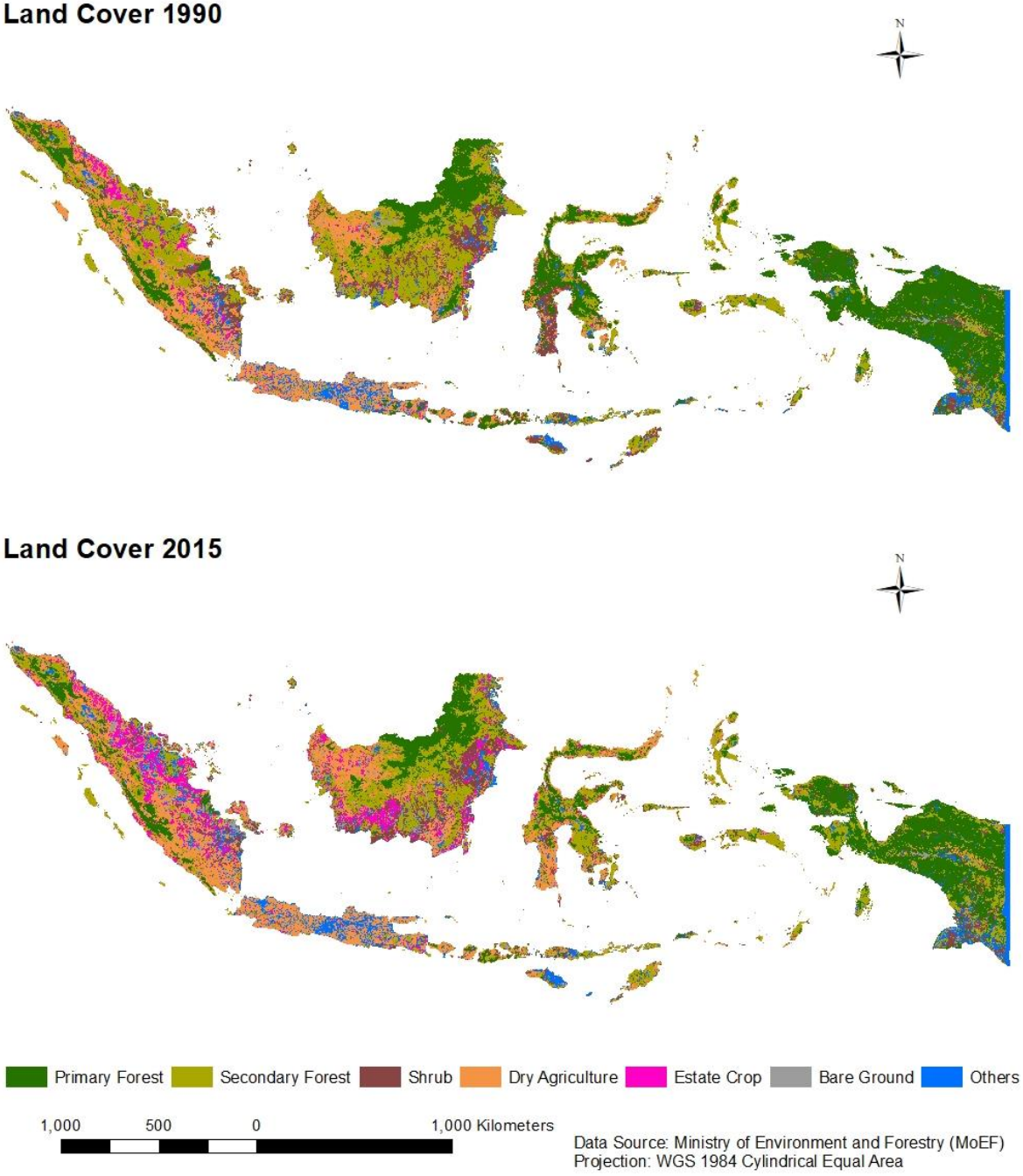

Figure S1. Land cover maps of Indonesia (1990 and 2015) with 7 grouped classes

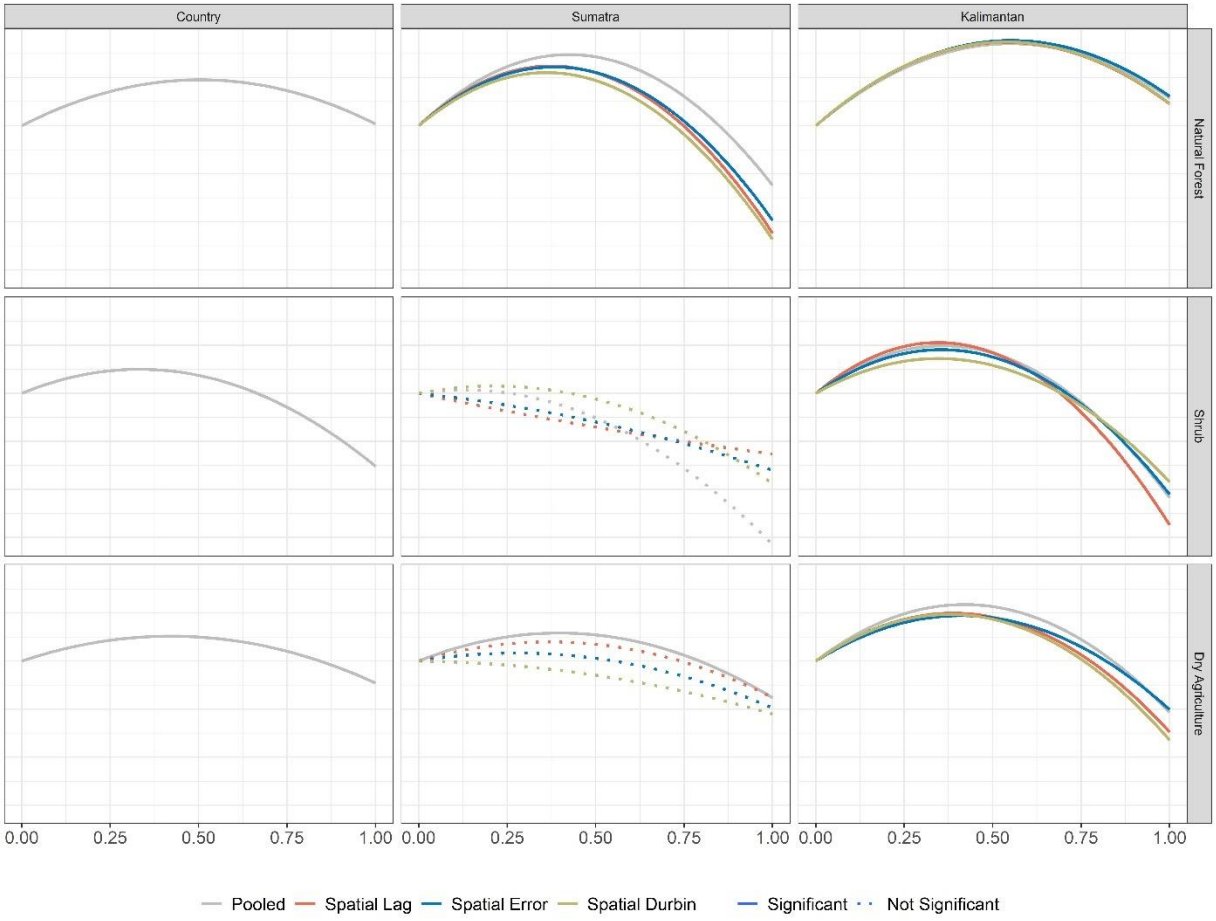

Figure S2. The polynomial relationship between oil palm expansion and source land ratio. On Sumatra, the inverted "U" shape relationship existed only in the expansion into natural forest for all models (inflection points at 0.361-0.424) and into dry agriculture for the pooled model (inflection points at 0.397).On Kalimantan, the inverted "U" shape relationship existed in all models, the inflection points are around 0.538-0.553 for natural forest, 0.346-0.359 for shrub, and 0.379-0.420 for dry agriculture.

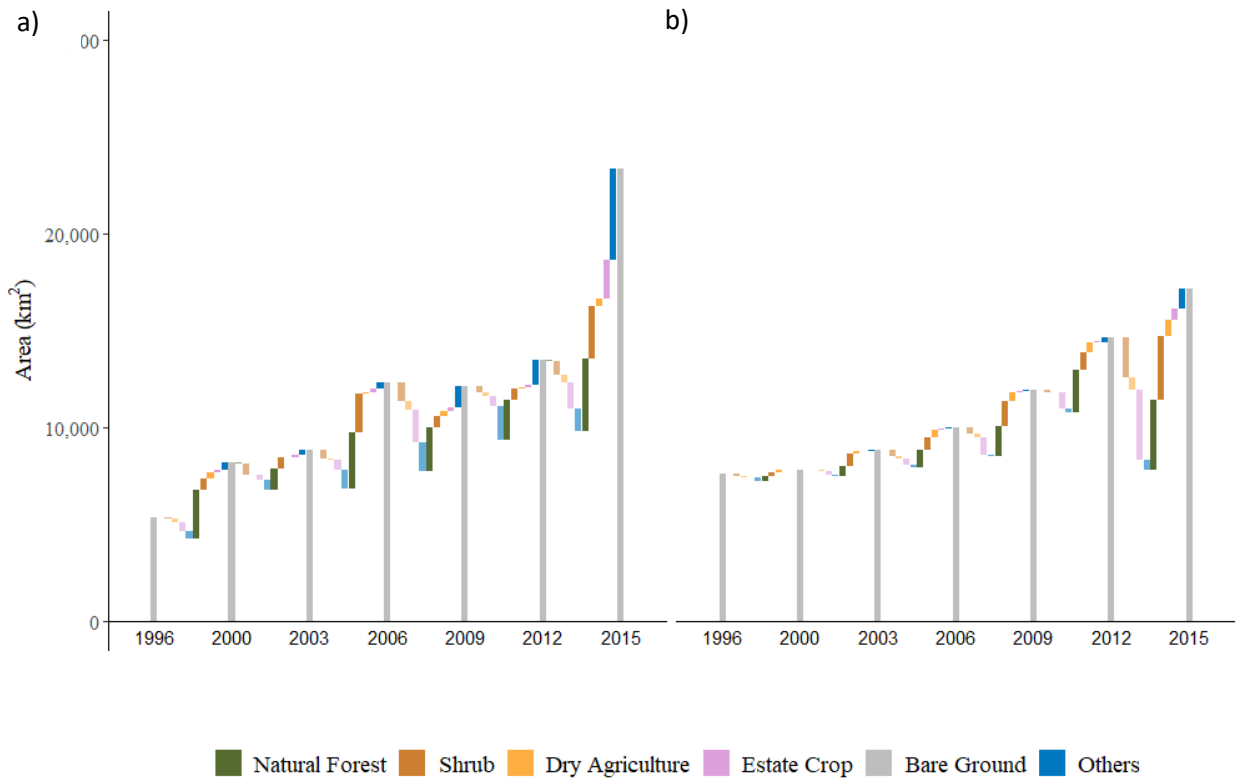

Figure S3. Direct conversions related to bare ground during 1996-2015. a) direct conversions related to bare ground in Sumatra; b) direct conversions related to estate crop in Kalimantan. The area of bare ground at each year are depicted by the bars cross the axis, while the floating bars depict the LULC changes among the seven classes. The increments indicate the inflows from other classes to bare ground, and the decrements indicate the outflows from bare ground to other LULC classes.

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