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Biophysical and socioeconomic drivers of oil palm expansion in Indonesia

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Abstract

Indonesia has been the largest supplier of palm oil since 2007 and now makes around 56% of the global market. While the existing literature paid major attention to the diverse impacts of oil palm plantation on socioeconomic factors and the environment, less is known on the joint role of biophysical and socioeconomic factors in shaping the temporal and spatial dynamics of oil palm expansion. This research investigates how the benefits and costs of converting other land use/cover (LULC) types to oil palm plantation affects the expansion patterns. It employs spatial panel modeling approach to assess the contributions of biophysical and socioeconomic driving factors. The modeling effort focuses on Sumatra and Kalimantan, two islands which have accounted for more than 90% of oil palm expansion in Indonesia since 1990, with Sumatra holding the majority of the country's plantations and Kalimantan having the highest growth rate since 2000. The results showed that the expansion in Kalimantan was strongly stimulated by export value of palm oil products, took place in areas with better biophysical suitability and infrastructure accessibility, followed the pecking order sequence that the more productive areas had already been taken by the existing agriculture and plantations, and avoided areas with high environmental values or socioeconomic costs. As demand for palm oil continues to grow and land resources becomes more limited, the expansion in Kalimantan will tend to approach the dynamics in Sumatra, with plantation expanding into remote and fertile area with high conversion cost or legal barriers. Bare ground seems to have served as a clearing-up tactic to meet the procedural requirements of oil palm plantation for sustainable development. The research facilitates the improved projection of areas prone to future expansion and the development of strategies to manage the leading drivers of LULC in Indonesia.

1. Introduction

Indonesia is the world's leader in palm oil production. Palm oil is the most widely consumed edible oil in the world (WWF, 2017). According to the U.S. Department of Agriculture (USDA, 2019a, b), the worldwide production of palm oil increased from 15 million tons to 70 million tons during 1995 to 2017 and Indonesia has been the largest supplier since 2007. Although oil palm cultivation has been questioned by the invasion of villagers' rights to resources (Inoue et al., 2013), intensifying conflicts with local people (Abram et al., 2017), and exacerbating social disparities (Obidzinski et al., 2014) and environmental inequity (Sheil et al., 2009), its positive impacts on economic growth and employment are notable. For example, the oil palm sector of Indonesia in 2017 employed 3.8 million people and produced about 39 million tons of palm oil from around 14 million ha of plantation areas across different regions of the country (USDA, 2019a, b; Directorate General of Plantation, 2018). The growth in oil palm plantation and production benefited the economic development in Indonesia remarkably and is believed to have lifted up to 2.6 million rural residents from poverty during 2000-2016 (Edwards, 2019). As the global palm oil market is expected to grow in the near future (Carter et al., 2007; Corley, 2009; Research and Markets, 2020), the rapid oil palm expansion will continue to be a major feature of land use and land cover (LULC) change in Indonesia.

However, the rapid expansion of oil palm has occurred and would continue to occur at the expense of other LULC, such as natural forests, shrub, and other agricultural land. Oil palm expansion in Indonesia is often criticized for resulting in deforestation and destruction of peatland (Koh et al., 2011). It was reported that approximately 80-85% of Indonesian deforestation in the 2000s occurred in Kalimantan and Sumatra (Hansen et al. 2009; Miettinen et al. 2011), two islands also holding over 90% of oil palm expansion during the same period (Abdullah, 2012; Wicke et al., 2011). More than 56% of oil palm expansion in Indonesia occurred at the expense of forests (Kho & Wilcove, 2008; Vijay et al., 2016), making it among the countries with highest rates of deforestation (Achard et al., 2004; Hansen, et al., 2009; Margono et al., 2014). Such loss of tropical and peat forests imposes severe damage to the environment, such as GHG emissions and biodiversity loss (Carnus et al., 2006; Koh & Wilcove, 2008; Koh et al., 2011).

Out of consideration of environmental protection, there are growing movements boycotting palm oil (European Union Parliament news, 2018). As the consumer pressure increased, actions were taken by local governments (e.g. forest moratorium, ISOP) (Indonesian President Instruction

no. 10, 2011; Indonesian President Instruction no. 6, 2013; Barthel et al., 2018), international organizations (e.g. REDD+, RSPO) (Koh & Butler, 2009; Von Geibler, 2013), and oil palm companies (United Nation, 2014; Butler, 2015). Several studies suggest that the trends of oil palm expansion have been shifted, with low-biomass land, such as shrub and dry agriculture, becoming major sources of estate crop expansion in recent years, and surpassing natural forest (Gunarso et al., 2013; Gaveau et al., 2016; Vijay et al., 2016; Austin et al., 2017; Austin et al., 2019). Meanwhile, Carlson et al. (2012, 2018) demonstrated that there is usually latency between land preparation and oil palm plantation, and a notable percentage of oil palm area is sourced from burned/cleared and bare lands in recent years.

Although a number of studies have analyzed LULC change of oil palm expansions (Koh & Wilcove, 2008; Hansen et al., 2009; Koh et al., 2011; Carlson et al., 2012a, b; Lee et al., 2014; Margono et al., 2014; Gaveau et al., 2016; Vijay et al., 2016; Austin et al., 2017; Austin et al., 2019) and provided reliable information on the types of LULC changes at different time points, they didn't explain why these changes occur with the observed patterns. Piker et al. (2016) and Vijay et al. (2016) assessed the biophysical suitability for oil palm plantation by identifying suitable ranges of climate, soil, and topography conditions and by using Global Agro-Ecological Zones (GAEZ) model as the suitability assessment tool, respectively. A handful of regional researches have investigated the biophysical and socioeconomic driving factors associated with observed oil palm plantations (Gatto et al., 2015; Castiblanco et al., 2013; Austin et al., 2015; Sumarga & Hein, 2016; Shevade & Loboda, 2019; and Ordway et al., 2019), with the aim to address biophysical suitability as well as market and infrastructure accessibility. However, these works were unable to examine the temporal dynamics of oil palm expansion and to reveal the role of economic benefits and costs in the conversion from other LULC types to oil palm, which should be fundamentally economic driven (Armsworth et al., 2006; Lim et al., 2019). The role of economic benefits and costs is particularly important in the context of Indonesia given the fact that more than 70% of palm oil production in the country is for exporting (Edwards, 2019; Rulli et al., 2019). The exception was Lim et al. (2019), which established a novel land rent modelling framework at the grid-cell level to address the role of potential economic returns of LULC conversion in explaining and predicting oil palm expansion in 2000, 2010 and 2015. Nevertheless, their model was unable to identify oil palm expansion in regions without prior plantations in 2000,

1 because the model employed only two simple variables¹ to capture the complex spatial contagion
2 effect as conceptualized in the von Thünen land rent theory (Angelsen, 2010).

3 Therefore, there is an urgent need for an effective modeling approach to uncover how
4 biophysical and socioeconomic factors have interactively driven the observed temporal and spatial
5 dynamics of oil palm expansion. To address this knowledge gap would help us to better understand
6 the coupled human and natural mechanisms that drive the dynamics and shape the patterns of oil
7 palm expansion, thus more effectively facilitating the projection of areas susceptible to future
8 expansion and the improvement of land use planning and governance so as to balance the increased
9 demand for palm oil products with the growing concerns of protecting tropical forest and its
10 ecosystem services.

11 In this research, we constructed spatial panel econometric models at the regency level
12 (secondary administrative level, roughly equivalent to a US county) to explain observed LULC
13 conversions in each 3 (or 4)-year time period over 1996-2015 and to demonstrate the major land
14 sources of oil palm expansion. Our modelling approach follows the economic theory that land-use
15 decision makers will choose a rate of conversion from one land-use type to another that maximizes
16 the present discounted value of a future stream of net benefits of conversion. We estimated the
17 gross economic benefits of land-use conversion to oil palm. This was done with the help of the
18 global agro-ecologic zone (GAEZ) model of the UN-FAO and IIASA (IIASA/FAO, 2012, 2019).
19 We proxied for fixed and variable costs of land-use conversion using a constant term and a linear
20 combination of biophysical variables which characterize the biophysical features of the regency.
21 To our best knowledge, this study is among the first to use panel data and spatial econometric
22 model to address the expansion patterns of oil palm in Indonesia.

23 24 **2. Materials and Method**

25 **2.1 Study Area**

26 Indonesia (6°08' N-11°15' S, 94°45' E-141°05' E), located in Southeast Asia, with more than
27 17,500 islands, covers approximate 1,904,569 km², is the largest island country of the world. It
28 has 34 provinces, and 282 regencies and municipalities (in 1996). The five main islands are

¹ The first variable relates to the proportion of cells devoted to oil palm surrounding each cell in the sample. The second variable refers to the percentage of plantation area within a buffer of 0.1° for cell i in period $t - 1$.

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3 1 Sumatra, Java, Kalimantan, Sulawesi and Papua. It has a population of 238 million (in 2010), 56%
4 2 of which is rural (FAO, 2011). The altitude varies from 0 m to 5,030 m above the sea level. The
5 3 climate is almost entirely tropical, the temperature ranges from 21°C to 33°C, and the average
6 4 annual precipitation is around 2,700 mm, varying from 1,300 mm in East Nusa Tenggara to 4,300
7 5 mm in parts of Papua (Bappenas, 2004), the wet season lasts from September to March while the
8 6 dry season lasts from March to August. Value added in agriculture makes around 14% of the gross
9 7 domestic product (GDP) (FAO, 2017), the major plants include food crops, such as rice and
10 8 secondary crops (maize, cassava, soybean, sweet potatoes, and peanut), and perennial crops,
11 9 including oil palm, rubber, coconut, coffee, cocoa, tea, etc. Palm oil is one of the most important
12 10 industries, employing about 2.4% of the total Indonesian workforce (in 2017) and contributing
13 11 fiscal and foreign exchange earnings to the country (Indonesia Investments, 2016; Directorate
14 12 General of Plantation, 2018). The Indonesian government has promoted oil palm cultivation as a
15 13 way to alleviate poverty and advance development in remote areas (Dharmawan et al., 2020; Li,
16 14 2016).

17 15 Sumatra and Kalimantan Islands are the two islands where more than 95% of oil palm
18 16 plantation of the country is located (Wicke et al., 2011). Sumatra, located in western Indonesia, is
19 17 the largest island entirely located in Indonesia, and the sixth-largest island in the world. It has a
20 18 territory of 473,481 km² and a population of 51 million (in 2010), with a tropical rainforest climate.
21 19 In 1996-2015, the annual average temperature is 26.6-27.1°C, and annual average rainfall is 2500-
22 20 3000mm. Kalimantan is the Indonesia portion of the Borneo Island, and comprises 73% of the
23 21 Island's area. It is the largest island of Indonesia, and has a territory of 544,105 km² and a
24 22 population of 14 million (in 2010), with a tropical rainforest climate. Generally speaking,
25 23 Kalimantan is cooler and wetter than Sumatra, the annual average temperature is 26.1-27.5°C, and
26 24 annual average rainfall is 2,700-3,500mm during 1996-2015.

27 25
28 26 2.2 The Spatial Panel Regression Model

29 27 We firstly constructed a pooled regression model to explain the observed patterns of oil palm
30 28 expansion. Our model followed the economic theory that the decision makers would convert other
31 29 land use types to estate crop plantation that maximizes the discounted value of net benefits
32 30 (revenue minus cost) of the conversion (Busch et al., 2012, 2015; Busch and Engelmann, 2018).
33 31 The gross economic benefits were first proxied by a linear combination of the estimated potential

yield of oil palm and the export value, and then corrected by the effects of major climate factors that contributed to the yearly variation of oil palm yield. The major climate factors include annual average temperature, shortwave radiation, annual precipitation and precipitation in the driest month. The cost of land conversion and transportation was proxied by a linear combination of slope, elevation, available water storage capacity (AWC) of soil, percent of protected area, percent of peatland, access time, population density and a second-order polynomial on source land cover (Mertens and Lambin 2000; Busch et al., 2012; Wheeler et al., 2013; Austin et al., 2015; Pirker et al., 2016). Existing publications demonstrated that previously established plantations had significant effects on conversions to estate crop plantation (Gaveau et al. 2009, Sumarga and Hein 2016; Shevade and Loboda, 2019), and fresh fruit bunches of oil palm have to be processed with 48 hours of harvesting to ensure oil quality (Furumo and Aide, 2017), thus we also included estate crop plantation fraction in 1990 and palm oil mill density as the explanatory variables. Among the explanatory variables, the export value, climate factors, protected area, population density and source land ratio are time variant, while the others, including potential yield of oil palm, estate crop plantations in 1990, palm oil mill density, access time, slope, elevation, AWC, and peatland percentage, are time invariant.

To summarize, the pooled regression model for estimating empirical relationships between the observed patterns of oil palm expansion and the variations in benefits and costs of such expansion is specified in the following equation, which shares similarity with the econometric models adopted in Busch & Engelmann (2015, 2018).

$$d_{it} = \exp(\beta_0 + \beta_1 A_i + \beta_2 X'_i + \beta_3 C'_{it} + \beta_4 P_{it} + \beta_5 Pop_{it} + \beta_6 S_{it} + \beta_7 S_{it}^2 + \beta_8 E_{t-1} + \varepsilon_{it}).$$

Where d_{it} is the area of oil palm expansion into each source land at regency i over year $t - 1$ and t . A_i is the potential yield per ha of oil palm plantation at regency i . X_i is a matrix of factors which are largely time-invariant and play significant role in determining the cost of land conversion and transportation, including biophysical and geographical factors such as slope, elevation, AWC, peatland percentage of regency i , as well as factors characterizing accessibility to market and infrastructure such as average access time to large cities, density of palm oil mills, and percentage of estate crop plantation in 1990 at regency i . C_{it} is a matrix of climate factors including annual precipitation, precipitation in the driest month, average annual temperature, and

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annual average shortwave radiation at regency i in year t . P_{it} is the percentage of regency i within a protected area in year t . Pop_{it} is the population density of regency i in year t . S_{it} is the source land ratio at regency i in year t , the second-order polynomial on S_{it} captures the non-linear trajectory of the expansion (Busch and Engelmann, 2015, 2018; Euler et al., 2017). E_{t-1} is the export value averaged over the previous time period because there are usually an approximately 3-year time delays between planning and actual planting of oil palm (Carlson et al., 2012; Gaveau et al., 2016). β_0 captures the unobserved constant determinants of estate crop expansion.

To address the latency between land preparation and oil palm plantation (Carlson et al., 2012; Carlson et al., 2018) and demonstrate the role of bare ground in the oil palm expansion process, we used Kalimantan as an example and ran the model using oil palm plus bare ground expansion as the dependent variable² first, and then ran the model using oil palm as the dependent variable and bare ground as the land source.

The pooled regression model is optimal and unbiased when the errors are independent, homoscedastic and serially uncorrelated. But for LULC change analysis, spatial autocorrelations typically exist among the observations (Elhorst, 2003), and for panel data, there are usually within-individual (pixel) correlations due to the traits of the individuals not represented by explanatory variables (Wooldridge, 2015). We employed spatial panel models to account for the individual heterogeneity and the spatial autocorrelation among regencies. The neighborhood relationship was defined by the contiguity-based method: two regencies were defined as neighbors if they shared a common border. We ran random effect rather than fixed effect regressions, because the time-invariant variables played important roles in oil palm expansion (Pirker et al., 2016). Spatially lagged dependent variable, spatial error autocorrelation and spatial Durbin models were included in the panel data regressions to account for the spatial dependencies in either dependent variables or unobserved variables (see Supplementary Information). We used Maximum likelihood approach to estimate the parameters in all the models (Elhorst, 2003). The “plm” and “splm” packages in R were used for the estimations of the pooled regression model and spatial panel econometric models (Croissant & Millo, 2008; Millo & Piras, 2012). Section S1 in Supplementary Information provides more technical details of the above spatial panel models.

² The choice of this combined dependent variable means that we treat bare ground expansion as a phase of oil palm expansion. We had run the regression using bare ground expansion as the dependent variable. The results are statistically similar to the results we reported hereafter (Table S6).

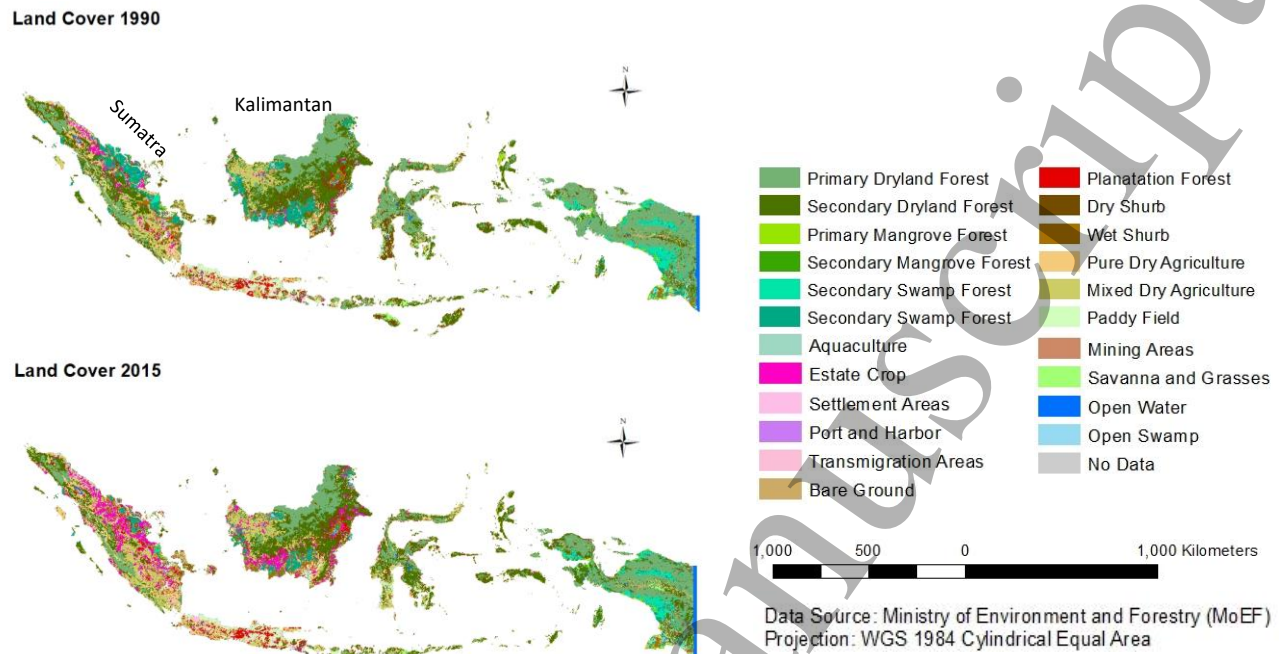


Fig. 1. Land cover maps of Indonesia (1990 and 2015)

2.3 Data

The LULC data for 1990-2015 were organized from Ministry of Forestry (MoFor) of Indonesia. The MoFor has used satellite data, particularly Landsat, for land cover mapping of Indonesia since 1990s. Up to now, LULC maps are available for the years of 1990, 1996, 2000, 2003, 2006, 2009, 2011, 2012, 2013, 2014 and 2015 with a spatial resolution of 30m×30m. We used the maps of 1990, 1996, 2000, 2003, 2006, 2009, 2012, and 2015 in our analysis, due to that it usually takes 2-4 years to allow for sufficient plant growth (Austin et al., 2019) and equal time interval is preferred in time series data (Brockwell et al., 1991), and in addition, the map of 1990 was used to present infrastructure associated with the previously established plantations. The land cover maps of Indonesia consist of 23 classes, including 6 classes of natural forest, 1 class of plantation forest, 15 classes of non-forest, and 1 class of no data (Fig. 1). We removed the class of no data and reclassified the other 22 classes into seven: primary forest, secondary forest, shrub, dry agriculture, estate crop, bare ground, and others. Table S1 in Supplementary Materials presents the correspondences between the 23 and 7 classes.

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1 The estate crop plantation class includes oil palm, rubber, coconut and other plantations.
2 Although oil palm plantation is not an independent class in these available maps, scattered
3 evidence from remote sensing researches demonstrates that the plantation of oil palm accounted
4 for about 62% of the total estate crop plantation in the country in 2014 (Petersen et al., 2016). As
5 highlighted in the previous section, the dependent variables in our panel models are the increments
6 of oil palm area. In this regard, data from the Statistical Yearbooks of Indonesia (Statistics
7 Indonesia, 1997-2016) and the Tree Crop Estate Statistics of Indonesia (Directorate General of
8 Plantation, 2013, 2015, 2017) show that around 89% of the estate crop plantations in the country
9 were contributed by oil palm during 1996-2015; and during 2007-2015, the corresponding
10 percentage was around 95% in Sumatra, while in Kalimantan, the expansion of oil palm accounted
11 for all of estate crop expansion. Therefore, when measuring the dependent variable, i.e., area of oil
12 palm expansion into each source land at regency i in year t , we directly use the area of estate crop
13 expansion as the best available proxy for oil palm expansion.

14 The potential yield of oil palm was collected from GAEZ v4 of IIASA and FAO at a spatial
15 resolution of $10\text{km} \times 10\text{km}$. The GAEZ provides an integrated agro-ecological assessment
16 methodology as well as a comprehensive global database for the characterization of climate, soil
17 and terrain conditions relevant to agricultural production (IIASA/FAO, 2012, 2019), and can be
18 used to assess the potential productivity of land under different management regimes. GAEZ is
19 widely used in the estimation of agricultural production potentials and yield gaps at the grid-cell
20 level (Tubiello and Fischer, 2007; Gohari et al., 2013; Piker et al., 2016; Zhong et al., 2019). We
21 used the potential yield of palm oil at high input level with natural rainfall as the input, since it is
22 the commonly used management strategy in oil palm plantation in Indonesia (Pirker et al., 2016).
23 Climatic factors, including annual average temperature, annual precipitation, precipitation of driest
24 month and shortwave radiation, were obtained and calculated from the WFDEI dataset ($50\text{km} \times$
25 50km) (Weedon et al., 2014). Export value from oil palm in each year were obtained from FAO
26 and were averaged over the observation (3-4 years) period and deflated to year 2000 USD.

27 We calculated the palm oil mills density from the Universal Mill List (UML) (World Resources
28 Institute, Rainforest Alliance, Proforest, and Daemeter, 2018). Access time data were organized
29 from A Global Map of Accessibility (Nelson, 2008), which describes the travel time to cities with
30 population larger than 50,000 in 2000 using land- or water-based means of travel and a cost-
31 distance algorithm, and is publicly available as 30 arc-second. The terrain data, including slope

1 and elevation were compiled using elevation data from the Shuttle Radar Topography Mission
 2 (NASA, 2009), which is publicly available as 3 arc-second (approximately 90 meters resolution at
 3 the equator) DEMs. AWC was extracted from the Harmonized World Soil Database (HWSD) (1
 4 km \times 1 km) (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012). Peatland percentage were calculated from
 5 peatland map collected by World Resources Institute (2012). Population density data were
 6 collected from Gridded Population of the World (GPW), which provides estimates of population
 7 density for every 5 years based on counts consistent with national censuses and population
 8 registers with respect to relative spatial distribution and adjusted to match United Nations country
 9 totals (CIESIN, 2016), and the spatial resolution is 1 km \times 1 km for 2000-2015, and 5 km \times 5 km
 10 for 1995. The population data were interpolated to match the study period. Protected area data
 11 were compiled from IUCN Category I-VI, point features were displayed as circles which
 12 represented the reported protected area size (WDPA, 2014). Source land ratios were calculated
 13 from the LULC maps, and natural forest ratios were calculated as the sum of primary forest and
 14 secondary forest.

15 Table S2 lists the variables, the description of the corresponding data, and data sources. Table
 16 S3 reports the measurement units and summary statistics of variables. Tables S4.1-S4.3 present
 17 the pairwise correlations between explanatory variables in the country, Kalimantan, and Sumatra
 18 models. Table S5 reports the variance inflation factors. All maps were projected to the same
 19 coordinate system, resampled and calculated at second administrative level using ArcGIS 10.5.

20 2.4 Limitations of the research

21 Some of the time-invariant variables we employed, such as palm oil mill density, access time
 22 to large cities, are not actually static over time because the proximity or accessibility would change
 23 with new establishments of processing mills, roads, population cluster, etc. Therefore, the effects
 24 of these variables showed by our models may not be precise, and any of these variables
 25 constraining oil palm plantation in the past may not continue to be a constraint in the future.
 26 Similarly, new constraints may emerge in the future, such as climate change (Paterson et al. 2017)
 27 and soil degradation (Guillaume et al., 2016). In addition, the assessments are limited by the quality
 28 of datasets used for this analysis. The accuracies of LULC maps and other maps have been
 29 constrained by the available techniques and socio-political hurdles in data collection. The

resolution and time scale of these maps will possibly influence the estimates of land use conversions and the effects of the driving forces.

3. Results and Discussion

3.1 Land use and land cover (LULC) change

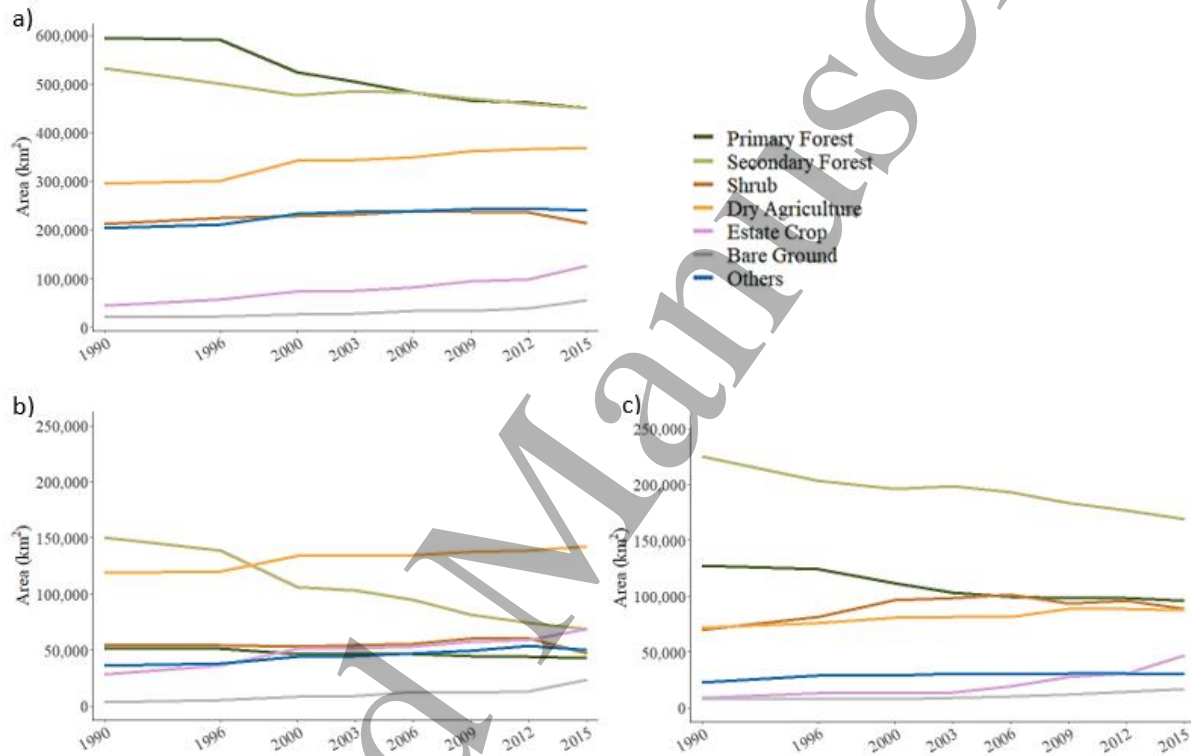


Figure 2. LULC change during 1990-2015. a) LULC change of the whole Indonesia; b) LULC change of Sumatra; c) LULC change of Kalimantan.

As shown in Figure 2a, natural forest decreased significantly from 1990 to 2015 in Indonesia. Primary forest decreased by approximately 24.3% (144,515 km²), with the rapidest degradation and deforestation during 1996-2000, then 2003-2006, 2000-2003, 2006-2009, and 2009-2015 in the order of decreasing pace. Of the 143,281 km² total decrease, 8,763 km² occurred in Sumatra and 31,653 km² occurred in Kalimantan, accounting for 16.9% and 24.8% of their primary forest in 1990 respectively. Although secondary forest received over 80% (125,037 km²) of primary forest conversions, it decreased by about 15.6% (82,524 km²) during 1990-2015. Indonesia lost

around 20% (227,039 km²) of its natural forest (primary plus secondary forest) in this period, with the highest deforestation rate (2.11%, 29,746 km²/year) in 1996-2000, a far second in 2006-2009 (1.00%, 9,512 km²/year), being followed by 2003-2006 (0.85%, 8,378 km²/year) and 2012-2015 (0.73%, 6,647 km²/year). Figure 2b-c shows the LULC changes in Sumatra and Kalimantan respectively. The two islands together made the majority of deforestation, around 65% (517,629 km²) of deforestation in Indonesia during 1996-2000 occurred in these two islands, the corresponding percentage jumped to 97% (408,017 km²) in 2009-2012, and fell back to 85% (392,845 km²) in 2012-2015. Sumatra lost 44.69% (90,206 km²) of its natural forest in 1990-2015 (Figure 2b), accounting for 39.7% of deforestation in the whole country, while 24.93% (87,907 km²) natural forest disappeared in Kalimantan during the same period (Figure 2c), accounting for 38.7% of deforestation in the whole country. The deforestation rate in Sumatra was consistently higher than the country average, the highest annual rates appeared in 1996-2000 (5.36%, 12,514 km²/year) and 2006-2009 (3.59%, 4,876 km²/year), when the El Nino events happened (1997 and 2006) (Field et al., 2016). Though the deforestation rate was consistently high and fluctuated, the total amount decreased as time went by, which is likely due to the long history of agriculture and plantation on the island (National Research Council, 1993; Wicke et al., 2008; Syuaib, 2016), which made the suitable land for productive use no longer covered by natural forest (Austin et al., 2017). The deforestation rates in Kalimantan were higher than the country average after 2000, when industrial oil palm plantation was widely introduced to the island (USDA, 2010).

Meanwhile, agriculture activities increased significantly (Figure 2). The area for dry agriculture had the largest increase in amount and estate crop had the rapidest expansion. Together with the area degraded to shrub and bare ground, they were the major drivers of deforestation in Indonesia. Estate crop area increased from less than 45,000 km² to more than 120,000 km² (Figure 2a), with an average annual speed of 4.24% (annual increase of 3,277 km²/year). The rapidest estate crop expansion occurred in 2012-2015 (with an average annual rate of 8.40%, or 9,089 km²/year), which was largely a result of the expansion occurred in Kalimantan (with an average annual rate of 15.47%, 5484 km²/year), followed by that in 1996-2000 (6.77%, 5,668 km²/year), mainly driven by the expansion in Sumatra (9.14%, 5,057 km²/year). Sumatra and Kalimantan together accounted for around 97% of the estate crop expansion in Indonesia during 1990-2015. Sumatra dominated the expansion before 2000 by contributing 77.1% of the national expansion during 1990-2000 (28,877 km², Figure 2b), while Kalimantan accounted for 63.67% of national

expansion after 2003 (51,645 km², Figure 2c), driven by the policy reforms in late 1990s which facilitated foreign direct investments in agriculture (Bissonnette 2015).

Natural forest, shrub, and dry agriculture are the three major direct land cover/use sources of estate crop expansion in Indonesia, as well as on the two islands (Figure 3). Shrub is the largest direct source of estate crop expansion in the country (Figure 3a), with a contributing share of 32.66% (27,289 km²), followed by natural forest (27.33%, 22,834 km²) and dry agriculture (21.45%, 17,924 km²). Natural forest was the largest direct source of estate crop expansion in Sumatra (Figure 3b), with a share of 33.59% (13,259 km²), whereas shrub contributed higher share as time went by and was the second largest source with a share of 23.83% (9,409 km²). In Kalimantan (Figure 3c), the trend is somehow different, as shrub accounted for 42.48% (16,318 km²) of all direct conversions to estate crop during 1996-2015 and was the largest source in 2000-2009 and 2012-2015. As time went by, estate crop expansion tended to occur on low-biomass land, such as shrub and dry agriculture, while natural forest became a less important direct source. Dry agriculture became a major source of estate crop expansion in both islands, especially during 2012-2015 (Figure 3b-c). The shifting patterns of estate crop expansion is consistent with those of Austin et al., who also reported a steadily declining share of oil palm plantations displacing natural forest. The shifting pattern could be explained by the following three reasons. (1) The conservation interventions by the government, NGOs and private sectors in oil palm industry (Indonesian President Instruction no. 10, 2011; Indonesian President Instruction no. 6, 2013; Koh & Butler, 2009; Von Geibler, 2013; United Nation, 2014; Butler, 2015; Barthel et al., 2018) are making some progress towards natural forest protection, although extending the protection to secondary forest is needed (Austin et al., 2015; Sumarga and Hein, 2016). (2) As the availability of suitable forestland become more limited, the estate crop expansion tends to occur by conversion of existing agricultural lands (Meyfroidt et al., 2014). (3) The smallholder, who need access to existing oil palm processing mills, prefers low-biomass land (Walker 2004; Meyfroidt et al., 2014).

There were sizeable conversions related to bare ground, especially in Sumatra and Kalimantan after 2000 (Figures 2 and 3, Figure S3). The major sources of bare ground establishment were secondary forest and shrub (Figure S3). Clearance of natural forest to bare ground made up a higher portion of deforestation as time went by on both islands (Figure S3). During 1996-2015, bare ground accounted for 12.03% (4,747 km²) and 15.30% (4,878 km²) of the direct sources of oil palm expansion in Sumatra and Kalimantan respectively (Figure 3), oil palm was the only major

productive sink of bare ground conversions in Kalimantan and the amount of conversion increased as time went by (Figure S3). As there is often a latency between land preparation and oil palm plantation (Carlson et al., 2012), bare ground might be an intermediate phase of oil palm expansion.



Figure 3. Direct conversions related to estate crop during 1996-2015. a) direct conversions related to estate crop in the whole country; b) direct conversions related to estate crop in Sumatra; c) direct conversions related to estate crop in Kalimantan. The area of estate crop at each year are depicted by the bars cross the axis, while the floating stacked bars depict the LULC changes among the seven classes. The increments indicate the inflows from other classes to estate crop, and the decrements indicate the outflows from estate crop to other LULC classes. The inflows are remarkably larger than the outflows.

3.2 Regression results

We first ran pooled regression models on oil palm expansion into the three major land sources in Indonesia during 1996-2015. The regression results, as shown in Table 2, indicated that the oil palm expansion in Indonesia tended to occur in regencies with longer access time to major cities, lower population density, gentler slope, medium level of source land ratio (owing to the inverted U-shape relationship), lower shortwave radiation, higher peatland percentage, and more significant presence of estate crop plantation in 1990. Higher export value in previous period ($t - 1$) was positively and significantly associated with a larger extend of oil palm expansion, supporting the proposition that oil palm expansion in Indonesia was largely driven by profitability of export (Armsworth et al., 2006; Lim et al., 2019). Therefore, as the global palm oil demand continues to grow (Research and Markets, 2020), oil palm plantation in Indonesia would continue to expand into both natural forest and low-biomass land. This positive stimulation effect was stronger on the expansion into low-biomass land cover/use types, such as dry agriculture and shrub, than into natural forest. Numerically speaking, an increase of 1 billion (2000) USD in export value in previous period would raise the oil palm expansion by 7.71%, 15.5%, and 20.2% into natural forest, shrub and dry agriculture, respectively.

We then ran pooled regression models for each of the two islands, Sumatra and Kalimantan. In order to address the possible individual heterogeneity and spatial autocorrelation issues of the pooled models, we further ran spatial panel random effect models in the forms of spatial lag, spatial error and spatial Durbin. Figure 4 visually presented the results of all these regressions for direct comparison. All the spatial panel models showed that there were significant positive spatial autocorrelations on both islands, the random effects were significantly more important compared to the idiosyncratic errors in Sumatra, but not in Kalimantan (Table in Figure 4). As shown in Figure 4, addressing the spatial autocorrelation did not change the direction, magnitude, and significance inference of the coefficients on individual explanatory variables in the natural forest models, but changed the significance inference of several explanatory variables in the shrub and dry agriculture models. In the shrub models, the effects of oil palm potential yield and driest month precipitation in Sumatra, as well as the effects of mill density in Kalimantan, were largely explained by the positive spatial autocorrelation in the explanatory variables, while the effects of access time in Kalimantan were largely due to the spatial autocorrelation among the oil palm

expansion. Meanwhile, the expansion into Kalimantan had a significant tendency to occur at area with lower available water capacity when the spatial autocorrelations of the explanatory variables were addressed. The effects of spatial autocorrelations were larger in the dry agriculture models of both islands and led to more remarkable changes among the explanatory variables in the models of Sumatra. When the spatial autocorrelation in Kalimantan were addressed, the coefficients on shortwave radiation became insignificant, while area with gentler slope were significantly preferred. For models of Sumatra, the expansion pattern is strongly associated with the significant positive spatial autocorrelation, except that area with little estate crop plantation in 1990 were significantly preferred by oil palm expansion into dry agriculture when the spatial autocorrelations among the explanatory variables were addressed.

Figure 4 showed that oil palm expansion on the two islands also tended to occur at area relatively more remote to major cities, which was different from the assumptions and results from some other researches (Pirker et al., 2016; Sumarga and Hein, 2016; Lim et al., 2019). This result could be explained by the location choice sequence of plantation developers in a way similar to the pecking order sequence of corporate managers in considering their sources of financing (Myers and Majluf, 1984; Vogt, 1994). It means that the suitable area with better access to major cities could already been taken by existing plantations, and the new plantation has to be located in more remote area than the existing ones.

A comparison of the results between the two islands showed some differences in the patterns of oil palm expansion. The establishment of oil palm plantation was earlier and the expansion was also faster before 2000 in Sumatra than in Kalimantan, while the expansion pace became faster in Kalimantan after 2003 (Figure 2b-c; USDA, 2013). Since Sumatra has a longer oil palm cultivation history and more intense agricultural activities (National Research Council, 1993; Wicke et al., 2008; Syuaib, 2016), the natural forest resources left for estate crop plantation has become limited (Figure 2b). Compared with Sumatra, Kalimantan was a later comer (Wicke et al., 2008; Austin et al., 2017) and land resources for oil palm expansion on the island was less limited (Figure 2c). Therefore, the expansion patterns of oil palm in Kalimantan were better characterized by our explanatory models than in Sumatra.

The direction and significance of the coefficients on individual explanatory variables in Kalimantan were more in line with our expectations, i.e., oil palm expansion would be stimulated by export value of palm oil products, and tend to occur at area with better biophysical suitability

1 and infrastructure accessibility as well as with low conversion cost. The stimulation effects of
2 export value were statistically significant and positive for oil palm expansion into each of the three
3 sources in Kalimantan, but not significant for the case of expansion into natural forest in Sumatra.
4 Oil palm expansion in Kalimantan, especially into natural forest, was more likely to occur in area
5 with more suitable climatic conditions, such as high shortwave radiation and higher precipitation
6 in the driest month. In country models and Kalimantan models, oil palm expansion showed an
7 inverted “U” shape relationship with each of the source land ratios, indicating that oil palm
8 expansion tended to occur at area within the medium range of the source ratio (Figure S2). This
9 finding was consistent with those of existing researches (Busch and Engelmann, 2015, 2018; Euler
10 et al., 2017). By contrast, on Sumatra island, such an inverted “U” shape existed in the expansion
11 into natural forest for all models and into dry agriculture for the pooled model (Figure S2). For the
12 infrastructure and market factors, the expansion in Kalimantan tended to benefit from existing
13 infrastructures as associated with the existing plantations and processing mills, and the beneficial
14 connection was more significant and stronger with expansion into natural forest. By contrast, the
15 plantation in 1990 and mill density did not constrain oil palm expansion into any sources in
16 Sumatra, since oil palm plantation and the associated infrastructure had already dispersed over the
17 island except for the mountainous area along the west coast. Places with lower population density
18 was preferred by oil palm expansion into all three land sources in Kalimantan, which could be
19 explained by that (1) oil palm was less labor intensive than alternative crops (Euler et al., 2017;
20 Feintrenie et al., 2010; Gatto et al., 2017), (2) places with higher population density and longer
21 history of planting traditional crops were less attractive for switching to oil palm (Gatto, et al.,
22 2015), and (3) oil palm companies intended to avoid land tenure conflicts and high transaction
23 costs associated with consolidating land from smallholders (Meyfroidt, et al., 2014). Nevertheless,
24 this relationship was significant in Sumatra for the expansion into shrub only. Percentage of
25 peatland showed opposite effects on oil palm expansion in Sumatra versus Kalimantan. The
26 negative relationship in Kalimantan might be because oil palm establishments on the island
27 preferred mineral land than peatland due to either the lower cost of land preparation or the intention
28 to reduce CO₂ emissions (Afriyanti et al., 2016; Meyfroidt, et al., 2014; Rulli et al., 2019).

29 Different from our expectation, potential yield of oil palm showed a negative effect on oil palm
30 expansion in Kalimantan, which could be explained by the location choice sequence of plantation
31 developers in a way similar to the pecking order sequence of corporate managers in considering

1 their sources of financing (Vogt, 1994): The area with higher potential yield of oil palm also holds
2 higher potential yield for other plantations such as dry agriculture crops and paddy field, thus those
3 area has already been taken by the existing agricultural activities and estate crop plantations.
4 Interestingly, such a pecking order effects were not found in Sumatra, which might be explained
5 by the following two reasons. First, comparing with Kalimantan where all source lands are
6 generally suitable for oil palm plantation with a potential yield ranging between 43-71 ton/ha, the
7 potential yield of oil palm in Sumatra ranges between 6-72 ton/ha with regencies along the west
8 coast being unsuitable for oil palm plantation at all. Second, because of the longer history of
9 plantation (National Research Council, 1993; Wicke et al., 2008; Syuaib, 2016), remaining land
10 resources for new plantation in Sumatra has become limited after 1990 (Figure 2b), as a result, oil
11 palm has to expand into area with relatively high potential yield but being very costly or illegal to
12 convert, such as peatland and logging concessions (USDA, 2010; Gaveau et al., 2013; Austin et
13 al, 2017), and the high share of smallholders (40%) aggravated the situation (Gatto et al., 2015;
14 Molenaar et al., 2013; Meyfroidt et al., 2014).

15 In our analysis at the regency level, protected area showed no significant effect on oil palm
16 expansion. However, we cannot conclude that protected area was not effective on protecting
17 natural forest from plantation expansion, because the spatial resolution at the regency level was
18 quite coarse, and protected area accounted for only a small portion of the territory of individual
19 regencies. To address the effects of protected area, analyses at the grid level are needed.

Table 1. Regression results of pooled models for expansion of oil palm into three major land sources in Indonesia

	Natural Forest			Shrub			Dry Agriculture		
	$\hat{\beta}$	t-value	sig.	$\hat{\beta}$	t-value	sig.	$\hat{\beta}$	t-value	sig.
(Intercept)	-114.400	-2.052	**	-77.669	-1.287		-43.563	-0.727	
Oil palm potential yield	0.015	1.542		0.034	3.246	***	0.039	3.661	****
Plantation in 1990	0.024	1.807	*	0.042	2.976	***	0.032	2.262	**
Mill density	-0.670	-1.495		-1.249	-2.560	**	-1.388	-2.873	***
Access time	2.249	5.174	****	1.864	5.001	****	1.092	2.704	***
Temperature	0.350	1.898	*	0.236	1.181		0.114	0.577	
Shortwave radiation	-0.026	-3.079	***	-0.035	-3.959	****	-0.026	-2.962	***
Precipitation	0.085	0.986		0.043	0.460		-0.093	-1.005	
Driest month precipitation	0.338	2.549	**	-0.282	-1.955	*	-0.114	-0.799	
AWC	-0.898	-0.257		-8.492	-2.177	**	-11.453	-3.053	***
Elevation	0.083	1.113		0.037	0.464		0.062	0.809	
Slope	-0.340	-5.642	****	-0.143	-2.475	**	-0.088	-1.556	
Source land ratio	18.928	13.426	****	15.081	6.888	****	12.282	7.494	****
Source land ratio ²	-18.751	-11.193	****	-22.664	-6.062	****	-14.568	-7.271	****
Population density	-0.109	-2.068	**	-0.142	-2.423	**	-0.093	-1.552	
Export value ($t - 1$)	0.077	3.720	****	0.155	6.874	****	0.202	9.085	****
Peatland %	0.089	7.913	****	0.089	7.390	****	0.081	6.942	****
Protected %	-0.018	-1.461		0.036	2.903	***	0.039	3.217	***
R ²	0.356			0.257			0.185		
AIC	11184.770			11516.140			11480.520		
Log Likelihood	-5573.384			-5739.071			-5721.262		

Notes: *, **, ***, and **** stand for the significant level of 10%, 5%, 1%, and 0.1%, respectively.

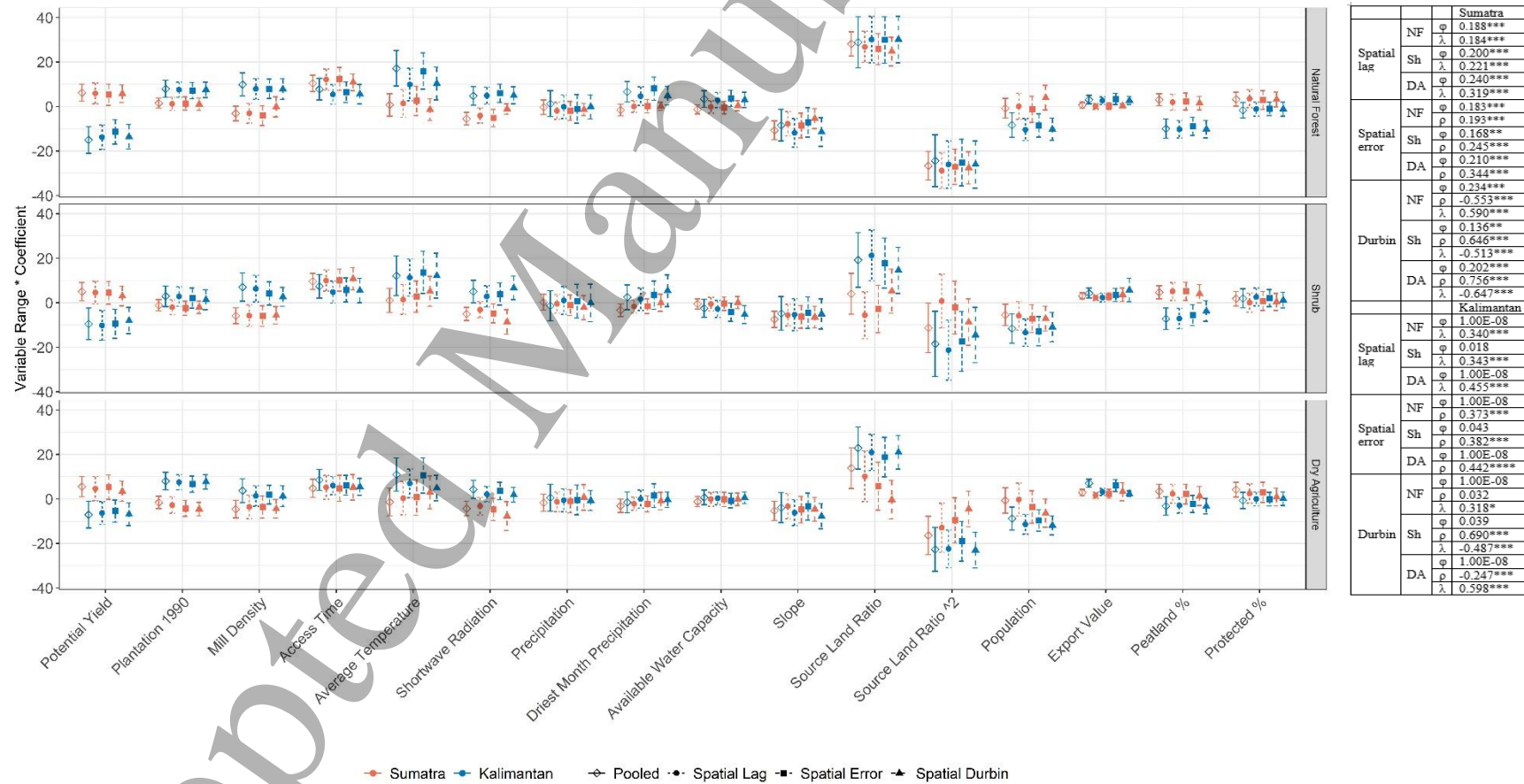


Figure 4. The spatial panel random effect model results for oil palm expansion in Sumatra and Kalimantan. Vertical pars correspond to 90% confidence intervals. The vertical axis (Variable Range × Coefficient) is the scaled coefficient, which can be used to make the coefficients comparable³. The table on the right shows the spatial autocorrelation statistics (λ for spatial lag, ρ for spatial error) and the random effect estimation (φ) of each model, *, **, ***, and **** stand for the significant level of 10%, 5%, 1%, and 0.1%, respectively.

³ To make the contributions of variables comparable, explanatory variables are scaled by range method: $variable\ range = variable_{max} - variable_{min}$, $Variable_{scaled} = \frac{Variable}{Variable\ Range}$, $Coef \times Variable = Coef_{scaled} \times Variable_{scaled}$, therefore, $Coef_{scaled} = Coef \times Variable\ Range$.

3.3. Bare ground as land banking of oil palm expansion in Kalimantan

Since oil palm is almost the only productive sink of bare ground conversion in Kalimantan, and there is often a latency between forest clearance and oil palm plantation (Carlson et al., 2018), we treated bare ground expansion as a phase of oil palm expansion, and ran the pooled and spatial panel models using oil palm and bare ground expansion together as the dependent variable first (Table 2). The results showed that bare ground developed from natural forest were clustered in areas with large protection portion, more natural forest cover, and less significantly stimulated by the export value of the previous period when spatial autocorrelation within explanatory variables were addressed. We then ran the pooled and spatial panel models using oil palm expansion as the dependent variable and bare ground as the land source (Table 3). The results indicated that the conversion from bare ground into oil palm plantation was significantly stimulated by the export value in the previous period, and the conversion was clustered in regencies with higher portion of protected area. Considering the fact that bare ground was developed and then converted to oil palm plantation at a rapid pace in recent years (Carlson et al., 2012a, b), the above results suggested that bare ground had been increasingly used as an indirect clearing-up tactic for the oil palm expansion at a later stage so that the expansion nominally meets the sustainable development requirements. The existence of this land banking mechanism highlights that it is practically important to include bare ground development into the monitoring system so that the system can more effectively track where and why bare ground is developed and what it ends up with. Meanwhile, as the current moratorium and RSPO certification only deals with new licenses and post-certification activities, it is necessary to establish policies to cope with such land banking.

Table 2. Results of pooled and spatial panel models for bare ground as land banking for oil palm 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)	-1014.906	-2.068		-694.287	-1.503		-970.531	-1.949		-915.913	-1.825	
Oil palm potential yield	-0.038	-0.285		-0.051	-0.389		0.020	0.176		0.033	0.304	
Plantation 1990	0.091	0.618		0.115	0.804		0.060	0.447		0.046	0.343	
Mill density	21.254	2.577	**	20.963	2.607	***	20.915	3.274	****	20.210	3.451	****
Access time	2.028	1.364		0.955	0.668		0.894	0.642		0.757	0.560	
Temperature	3.330	2.012	**	2.280	1.464		3.153	1.882	*	2.948	1.747	*
Shortwave radiation	0.046	0.788		0.044	0.787		0.086	1.510		0.110	1.877	*
Precipitation	-0.178	-0.362		-0.195	-0.429		-0.314	-0.575		-0.306	-0.536	
Driest month precipitation	1.285	2.417	**	0.981	2.039	**	1.872	2.984	***	2.104	3.155	***
AWC	28.636	0.997		12.244	0.442		0.964	0.035		-0.852	-0.031	
Slope	-0.331	-0.712		-0.506	-1.133		-0.330	-0.789		-0.337	-0.835	
Source land ratio	14.844	1.928	*	15.691	2.183	**	18.570	2.778	***	17.478	2.752	***
Source land ratio ²	-11.746	-1.398		-11.972	-1.523		-12.665	-1.786	*	-11.134	-1.684	*
Population density	-11.621	-4.368	****	-12.338	-4.888	****	-11.312	-4.541	****	-10.040	-4.024	****
Export value ($t - 1$)	0.209	2.299	**	0.144	1.758	*	0.212	1.503		0.303	1.480	
Peatland	-0.091	-2.476	**	-0.103	-2.878	***	-0.096	-2.864	***	-0.085	-2.541	**
Protected %	0.124	1.514		0.149	1.868	*	0.153	2.235	**	0.127	1.963	**
phi				0.033	0.595		1.00E-08	NA		1.00E-08	NA	
rho							0.500	6.857	****	0.688	8.062	****
lambda				0.396	5.167	****				-0.350	-2.218	**
R ²	0.367											
AIC	1442.376			1487.258			1475.436			1473.288		
Log Likelihood	-703.188			-691.629			-685.718			-683.644		

Notes: *, **, ***, and **** stand for the significant level of 10%, 5%, 1%, and 0.1%, respectively.

1 Table 3. Results of pooled and spatial panel models of oil palm expansion into bare ground 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)	-926.470	-1.977	**	-1088.743	-2.526	**	-1266.301	-2.602	***	-1150.240	-2.211	**
Oil palm potential yield	-0.190	-1.347		-0.226	-1.732	*	-0.220	-1.828	*	-0.209	-1.876	*
Plantation 1990	-0.020	-0.126		-0.058	-0.397		-0.096	-0.642		-0.080	-0.529	
Mill density	24.908	2.886	***	26.774	3.350	****	22.057	3.302	****	16.251	2.792	***
Access time	1.440	0.971		0.753	0.550		0.982	0.680		1.035	0.709	
Temperature	3.093	1.969	*	3.683	2.549	**	4.227	2.593	***	3.774	2.167	**
Shortwave radiation	0.054	0.913		0.000	0.005		0.058	0.985		0.141	2.210	**
Precipitation	-0.674	-1.326		-0.397	-0.853		-0.356	-0.636		-0.359	-0.585	
Driest month precipitation	0.815	1.410		0.658	1.255		0.973	1.485		1.126	1.551	
AWC	-36.322	-1.289		-36.259	-1.394		-45.970	-1.671	*	-49.287	-1.788	*
Slope	-0.484	-1.107		-0.436	-1.080		-0.356	-0.920		-0.418	-1.100	
Source land ratio	77.657	1.571		78.387	1.737	*	74.354	1.752	*	55.052	1.427	
Source land ratio2	-722.346	-1.716	*	-729.778	-1.909	*	-642.298	-1.766	*	-452.203	-1.369	
Population density	-9.735	-3.588	****	-10.846	-4.345	****	-10.020	-3.834	****	-9.211	-3.432	****
Export value	0.500	4.866	****	0.258	2.772	***	0.408	2.999	***	0.630	2.924	***
Peatland	-0.145	-3.965	****	-0.146	-4.309	****	-0.143	-4.199	****	-0.129	-3.766	****
Protected %	0.213	2.335	**	0.253	2.996	***	0.236	3.031	***	0.180	2.475	**
phi				8.14E-03	0.245		1.44E-03	0.078		0.011	0.332	
rho							0.399	5.688	****	0.665	7.905	****
lambda				0.340	4.887	****				-0.408	-2.920	***
R2	0.373											
AIC	1478.492			1524.830			1518.596			1515.214		
Log Likelihood	-721.246			-710.415			-707.298			-704.607		

2 Notes: *, **, ***, and **** stand for the significant level of 10%, 5%, 1%, and 0.1%, respectively.

4. Conclusion

Oil palm expansion is one of the major drivers of deforestation in Indonesia, especially in Sumatra and Kalimantan. However, as time goes by, the expansions become more likely to occur at low-biomass area, such as shrub and dry agriculture, than natural forest. Bare ground often emerges as an intermediate state (i.e., land banking) of conversion from natural forest to oil palm plantation, serving as a clearing-up tactic to meet the procedural sustainable development requirements of oil palm plantation.

Most of the plantation expansion during our study period occurred in Sumatra and Kalimantan, the two islands holding the majority of oil palm plantation in Indonesia. Compared with Sumatra, Kalimantan is at an earlier stage of plantation development with relatively abundant land resources. Consequently, oil palm expansions in Kalimantan are better characterized by our models, meaning that the direction and significance of the coefficients on most of the explanatory variables meet the theoretical expectations which underlie the specification of our models. The results of our spatial panel regressions showed that oil palm expansion in Kalimantan was highly stimulated by export value of oil palm products, took place in area with better biophysical suitability and infrastructure accessibility, followed the pecking order sequence that the more productive areas had already been taken by the existing agricultural activities and estate crop plantations, and avoided area with high environmental values or socioeconomic costs.

However, as global demand for palm oil products continues to grow at a fast pace which in turn drives up export value, oil palm plantation will continue to expand, subject to the increasing scarcity of land sources. This trend may drive the expansion dynamics in Kalimantan in near future to approach that in Sumatra today, where oil palm plantation has been expanding into remote and fertile area with high conversion cost or legal barriers, including peatland and logging concessions which is limited by infrastructure accessibility. Under this highly plausible development scenario, future oil palm expansion in Indonesia would cause more environmental and social issues, such as increasing CO₂ emissions resultant from LULC conversion, failure of land concessions, land right conflicts, etc. Therefore, to balance oil palm expansion and environment conservation in Indonesia, the current regulations, such as forest moratorium, RSPO certification, protected area, land use concessions, zero-deforestation commitment, should be continued, extended to secondary forest and vulnerable ecosystems, as well as fully implemented and enforced. New policies on peatland protection and land banking regulation are urgently needed.

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