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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 supplies around 56% of the global market. While the existing literature has paid serious attention to the diverse impacts of oil palm plantation on socioeconomic factors and the environment, less is known about 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/ land cover (LULC) types to oil palm plantation affects these expansion patterns. We employ a spatial panel modeling approach to assess the contributions of biophysical and socioeconomic driving factors. Our modeling 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 show that the expansion in Kalimantan, which has been strongly stimulated by the export value of palm oil products, has occurred in areas with better biophysical suitability and infrastructure accessibility, following the 'pecking order' sequence, whereby more productive areas are already occupied by existing agriculture and plantations, and avoiding areas with high environmental values or socioeconomic costs. As demand for palm oil continues to grow, and land resources become more limited, the expansion in Kalimantan will tend towards the dynamics observed in Sumatra, with plantation expanding into remote and fertile areas with high conversion costs 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. This research facilitates the improved projection of potential areas liable 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, 2019b), the worldwide production of palm oil increased from 15 million tons to 70 million tons from 1995–2017, and Indonesia has been the largest supplier since 2007. Although oil palm cultivation has been questioned in relation to 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 (Directorate General of Plantation 2018, USDA 2019a, 2019b). The growth in oil palm plantation and production was significantly beneficial to economic development in Indonesia, and is believed to have lifted up to 2.6 million rural residents out of poverty in the period from 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), 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 will 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 the destruction of peatland (Koh *et al* 2011). It has been 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 which also underwent oil palm expansion of over 90% during the same period (Wicke *et al* 2011, Abdullah 2012). More than 56% of oil palm expansion in Indonesia occurred at the expense of forests (Kho and Wilcove, 2008, Vijay *et al* 2016), placing it among those countries with the highest rates of deforestation (Achard *et al* 2004, Hansen *et al* 2009, Margono *et al* 2014). This level of reduction in tropical and peat forests imposes severe damage on the environment, resulting in increased Greenhouse Gas emissions and biodiversity loss (Carnus *et al* 2006, Koh and Wilcove 2008, Koh *et al* 2011).

Out of consideration for environmental protection, there is a growing movement advocating the boycotting of palm oil (European Union Parliament news, 2018). As consumer pressure has increased, action has been taken by local governments (e.g., the forest moratorium, Indonesian Sustainable Palm Oil) (Indonesian President Instruction no. 10 2011, Indonesian President Instruction no. 6 2013, Barthel *et al* 2018), international organizations (e.g. REDD+, Roundtable on Sustainable Palm Oil) (Koh and Butler 2009, Von Geibler 2013), and oil palm companies (United Nation, 2014, Butler 2015). Several studies suggest that the trend of oil palm expansion has shifted, with low-biomass land areas, such as shrub and dry agriculture, becoming major sources of estate crop expansion in recent years, surpassing natural forest (Gunarso *et al* 2013, Gaveau *et al* 2016, Vijay *et al* 2016, Austin *et al* 2017, 2019). Meanwhile, Carlson *et al* (2012a, 2012b, 2018) have demonstrated that there is usually latency between land preparation and oil palm plantation, and a notable percentage of land for oil palm cultivation has been sourced from burned/cleared and bare land in recent years.

Although a number of studies have analyzed LULC changes with respect to oil palm expansion (Koh and Wilcove 2008, Hansen *et al* 2009, Koh *et al* 2011, Carlson *et al* 2012a, 2012b; Lee *et al* 2014, Margono *et al* 2014, Gaveau *et al* 2016, Vijay *et al* 2016, Austin *et al* 2017, 2019), and have provided reliable information regarding the types of LULC change at different time points, they did not explain why these changes occur in the patterns they observed. Piker *et al* (2016) assessed the nature of biophysical suitability for oil palm plantation by identifying suitable ranges of climate, soil, and topographical conditions, and Vijay *et al* (2016) used the Global Agro-ecological Zones (GAEZ) model as the suitability assessment tool. A handful of regional research articles have investigated the biophysical and socioeconomic driving factors associated with specific oil palm plantations (Castiblanco *et al* 2013, Gatto *et al* 2015, Austin *et al* 2015, Sumarga and Hein 2016, Shevade and Loboda 2019, Ordway *et al* 2019), with the aim of addressing biophysical suitability as well as market and infrastructure accessibility. However, these works were unable to examine the temporal dynamics of oil palm expansion, or to reveal the role of economic benefits and costs in the conversion from other LULC types to oil palm cultivation, which should be fundamentally economically 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 export (Edwards 2019, Rulli *et al* 2019). The exception in research terms is Lim *et al* (2019), who 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 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, because the model employed only two simple variables[3] to capture the complex spatial contagion effect, as conceptualized in the von Thünen land rent theory (Angelsen 2010).

Therefore, there is an urgent need for an effective modeling approach to uncover how biophysical and socioeconomic factors have interactively driven the observed temporal and spatial dynamics of oil palm expansion. To address this knowledge gap would help us to better understand the coupled human and natural mechanisms driving these dynamics and shaping the patterns of oil palm expansion, thereby more effectively facilitating the projection of areas susceptible to future expansion, and the improvement of land use planning and governance, so as to balance the increased demand for palm oil products with the growing concern for protecting tropical forests and their associated ecosystems.

In this research, we have constructed spatial panel econometric models at the regency level (secondary administrative level, roughly equivalent to a US county) to explain the observed LULC conversions for each 3 (or 4) year time period from 1996–2015, and to demonstrate the major land sources for oil palm expansion. Our modelling approach follows the economic theory that land-use decision makers will

[3] 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 $t-1$.

choose a rate of conversion from one land-use type to another on the basis of maximizing the present discounted value of a future stream of net benefits of conversion. We estimated the gross economic benefits of land-use conversion to oil palm. This was accomplished with the help of the GAEZ model formulated by the UN-FAO and IIASA (IIASA/FAO 2012, 2019). We proxied for fixed and variable costs of land-use conversion using a constant term and a linear combination of the biophysical variables which characterize the biophysical features of the regency. To the best of our knowledge, this study is among the first to use panel data and spatial econometric modeling to address the expansion patterns of oil palm cultivation in Indonesia.

2. Materials and method

2.1. Study Area

Indonesia (6°08′ N-11°15′ S, 94°45′ E-141°05′ E), is located in Southeast Asia, and with more than 17 500 islands, covering approximately 1 904 569 km^2, is the largest island country in the world. It has 34 provinces, and 282 regencies and municipalities (as of 1996). The five main islands are Sumatra, Java, Kalimantan, Sulawesi and Papua. It has a population of 238 million (as of 2010), 56% of which is rural (FAO 2011). The land altitude varies from 0 m to 5030 m above sea level. The climate is almost entirely tropical, with temperatures ranging from 21 °C to 33 °C, and the average annual precipitation is around 2700 mm, varying from 1300 mm in East Nusa Tenggara to 4300 mm in parts of Papua (Bappenas 2004). The wet season lasts from September until March, while the dry season lasts from March until August. Value added in agriculture constitutes around 14% of the gross domestic product (FAO 2017), with major cultivation areas including food crops, such as rice and secondary crops (maize, cassava, soybean, sweet potatoes, and peanut), and perennial crops, including oil palm, rubber, coconut, coffee, cocoa, tea, etc. Palm oil production is one of the most important industries, employing about 2.4% of the total Indonesian workforce (as of 2017) and contributing fiscal and foreign exchange earnings to the country (Directorate General of Plantation 2018; Indonesia-Investments 2017). The Indonesian government has promoted oil palm cultivation as a way to alleviate poverty and advance development in remote areas (Li 2016, Dharmawan *et al* 2020).

Sumatra and Kalimantan are the two islands where more than 95% of the oil palm plantations in the country are located (Wicke *et al* 2011). Sumatra, located in western Indonesia, is the largest island entirely located in Indonesia, and the sixth-largest island in the world. It has a territory of 473 481 km^2, a population of 51 million (in 2010), and a tropical rainforest climate. Between 1996 and 2015, the annual average temperature measured from 26.6 °C–27.1 °C, and the annual average rainfall was 2500–3000 mm. Kalimantan is the Indonesian portion of Borneo Island, and comprises 73% of the Island's area. It is the largest island in Indonesia, and has a territory of 544 105 km^2, a population of 14 million (in 2010), and a tropical rainforest climate. Generally speaking, Kalimantan is cooler and wetter than Sumatra, with an annual average temperature from 26.1 °C–27.5 °C, and an annual average rainfall of 2700–3500 mm from 1996–2015.

2.2. The Spatial Panel Regression Model

We firstly constructed a pooled regression model to explain the observed patterns of oil palm expansion. Our model followed the economic theory that the decision makers will convert other land use types to estate crop plantation so as to maximize the discounted value of net benefits (revenue minus cost) of the conversion (Busch *et al* 2012, 2015, Busch and Engelmann 2018). The gross economic benefits were first proxied via a linear combination of the estimated potential yield of oil palm and its export value, and then corrected based on the impact of major climate factors contributing to yearly variations in oil palm yield. These 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 via a linear combination of slope, elevation, available water storage capacity (AWC) of soil, percentage of protected area, percentage 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 have 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 that fresh fruit bunches of oil palm require to be processed with 48 h of harvesting to ensure oil quality (Furumo and Aide 2017), taking this into account, we also included the estate crop plantation fraction in 1990 and palm oil mill density as the explanatory variables. Of these explanatory variables, export value, climate factors, protected area, population density, and source land ratio are time variant, while 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 the empirical relationships between the observed patterns of oil palm expansion and the variations in benefits and costs of such expansion are specified in the following equation, which shares similarities with the econometric models adopted in Busch *et al* (2015) and Busch and Engelmann (2018).

$$d_{it} = \exp\left(\beta_0 + \beta_1 A_i + \beta_2 X_i' + \beta_3 C_{it}' + \beta_4 P_{it} + \beta_5 \mathrm{Pop}_{it} + \beta_6 S_{it} + \beta_7 S_{it}^2 + \beta_8 E_{t-1} + \varepsilon_{it}\right)$$

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 which play a 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 the 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 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, and the second-order polynomial on S_{it} captures the non-linear trajectory of the expansion (Busch *et al* 2015, Euler *et al* 2017, Busch and Engelmann 2018). E_{t-1} is the export value, averaged over the previous time period, because there is usually a time delay of approximately 3 years between the planning and the actual planting of oil palm (Carlson *et al* 2012a; 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* 2012a, 2018), and to demonstrate the role of bare ground in the oil palm expansion process, we used Kalimantan as an example, and began by running the model using oil palm plus bare ground expansion as the dependent variable[4], then running 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. However, for LULC change analysis, spatial autocorrelations typically exist among the observations (Elhorst 2003), and with respect to panel data, there are usually individual (pixel) correlations due to the traits of those individuals not represented by explanatory variables (Wooldridge 2015). We employed spatial panel models to account for individual heterogeneity and spatial autocorrelation between 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, since time-invariant variables play important roles in oil palm expansion (Pirker *et al* 2016). Spatially lagged dependent variables, 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 (available online at stacks.iop.org/ERL/16/034048/mmedia)). We used the 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 and Millo 2008, Millo and Piras 2012). Section S1 in the supplementary information provides more technical details regarding the above spatial panel models.

2.3. Data

The LULC data for the period 1990–2015 were acquired from the Ministry of Environment and Forestry (MoFor) of Indonesia. The MoFor has used satellite data, particularly Landsat, for land cover mapping of Indonesia since the 1990s. To date, LULC maps are available for 1990, 1996, 2000, 2003, 2006, 2009, 2011, 2012, 2013, 2014 and 2015, at a spatial resolution of 30 × 30 m. We used maps from 1990, 1996, 2000, 2003, 2006, 2009, 2012, and 2015 in our analysis, given that it usually takes 2–4 years to allow for sufficient plant growth (Austin *et al* 2019) and an equal time interval is preferred in time series data (Brockwell *et al* 1991); in addition, the map of 1990 was used to present infrastructure associated with 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 (figure 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 the supplementary material presents the correspondences between the original 23 classes and the reclassified 7 classes.

The estate crop plantation class includes oil palm, rubber, coconut, and other plantations. Although oil palm plantation is not an independent class in terms of the available maps, scattered evidence from remote sensing research demonstrates that the plantation of oil palm accounted for about 62% of the total estate crop plantation in the country in 2014 (Petersen *et al* 2016). As highlighted in the previous section, the dependent variables in our panel models are the increments in oil palm area. In this regard, data from the Statistical Yearbooks of Indonesia (Statistics Indonesia 1997–2016) and the Tree Crop Estate Statistics of Indonesia (Directorate General of Plantation

[4] 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).

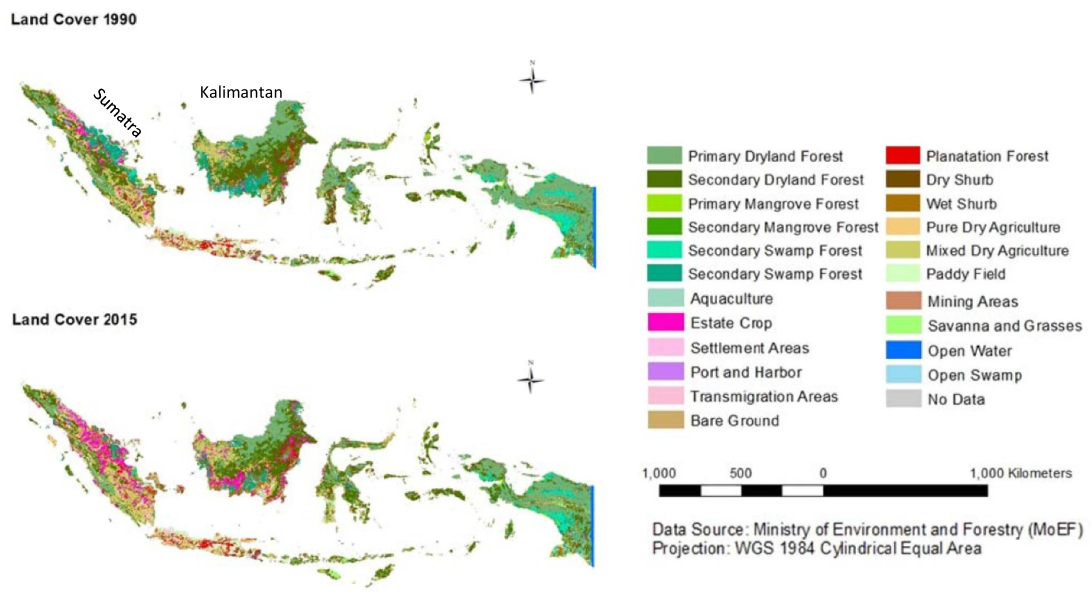


Figure 1. Land cover maps of Indonesia (1990 and 2015).

2013–2018) show that around 89% of the estate crop plantations in the country were attributed to oil palm from 1996–2015; from 2007–2015, the corresponding percentage was around 95% in Sumatra, while in Kalimantan, the expansion of oil palm accounted for the entirety of estate crop expansion. Therefore, when measuring the dependent variable, i.e., the area of oil palm expansion into each source land at regency *i* in year *t*, we directly use the area of estate crop expansion as the best available proxy for oil palm expansion.

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

We calculated the palm oil mill density based on the Universal Mill List (World Resources Institute, Rainforest Alliance, Proforest, and Daemeter, 2018). Access time data were organized on the basis of A Global Map of Accessibility (Nelson, 2008), which describes the travel time to cities with populations larger than 50 000 in 2000 using land- or water-based means of travel and a cost-distance algorithm, and is publicly available as 30 arc-second. The terrain data, including slope and elevation were compiled using elevation data from the Shuttle Radar Topography Mission (NASA, 2009), which is publicly available as 3 arc-second (approximately 90 m resolution at the equator) Digital Elevation Models (DEMs). AWC was extracted from the Harmonized World Soil Database (1 × 1 km) (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012). Peatland percentages were calculated from the peatland maps collatedby the World Resources Institute (2012). Population density data were collected from the Gridded Population of the World, which provides estimates of population density every 5 years, based on counts consistent with national censuses and population registers with respect to relative spatial distribution, and adjusted to match United Nations country totals (CIESIN, 2016); here, the spatial resolution is 1 × 1 km for 2000–2015, and 5 × 5 km for 1995. The population data were interpolated to match the study period. Protected area data were compiled from IUCN Category I–VI, where point features are displayed as circles, representing the reported protected area size (WDPA, 2014). Source land ratios were calculated from the LULC maps, and natural forest ratios were calculated as the sum of primary forest and secondary forest.

Table S2 lists the variables, the description of the corresponding data, and data sources. Table S3

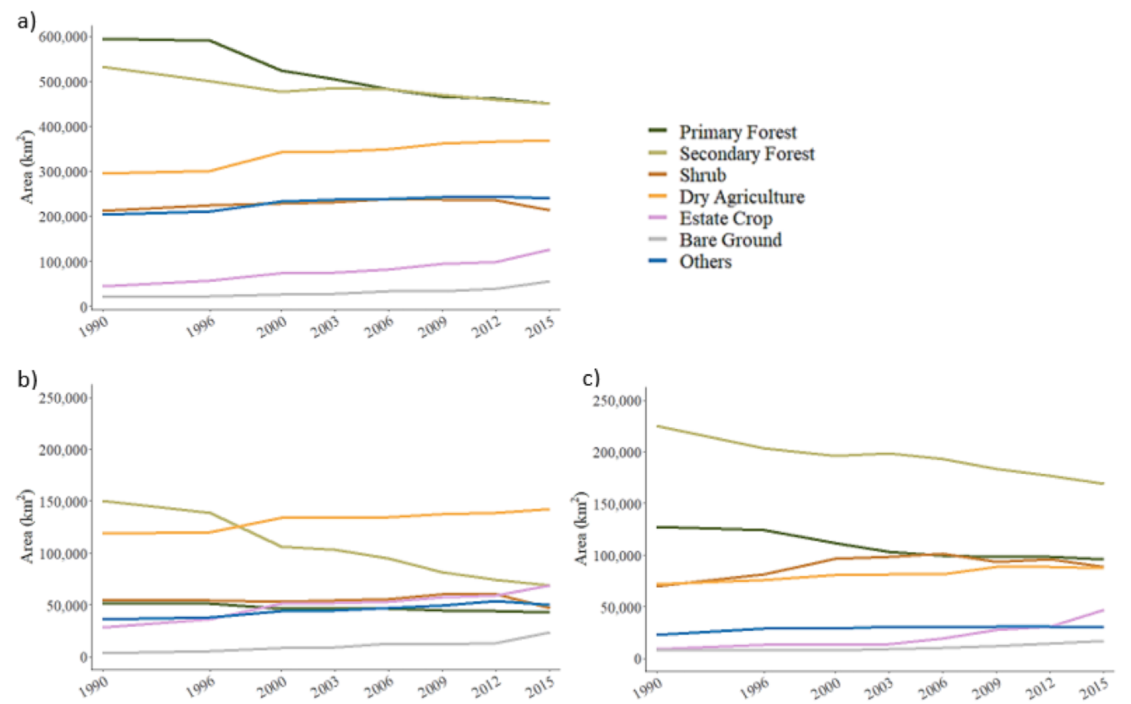


Figure 2. LULC change during 1990–2015. (a) LULC change for the whole Indonesia; (b) LULC change on Sumatra; (c) LULC change in Kalimantan.

reports the measurement units and summary statistics of variables. Tables S4.1–S4.3 present the pairwise correlations between explanatory variables in the country, Sumatra, and Kalimantan models. Table S5 reports the variance inflation factors. All maps were projected to the same coordinate system, resampled, and calculated at second administrative level, using ArcGIS 10.5.

2.4. Limitations of the research

Some of the time-invariant variables we employed, such as palm oil mill density, or access time to large cities, are not actually static over time because the proximity or accessibility would change with the establishment of new processing mills, roads, population clusters, etc. Therefore, the effects of these variables as shown by our models may not be precise, and any of these variables constraining oil palm plantation in the past may not continue to be a constraint in the future. Similarly, new constraints may emerge in the future, such as climate change (Paterson *et al* 2017) and soil degradation (Guillaume *et al* 2016). In addition, the assessments are limited by the quality of the datasets used for this analysis. The accuracies of LULC maps and other maps have been constrained by the available techniques and socio-political hurdles with respect to data collection. The resolution and time scale of these maps will possibly influence the estimates of land use conversions and the effects of their driving forces.

3. Results and discussion

3.1. Land use and land cover (LULC) change

As shown in figure 2(a), natural forest decreased significantly between 1990 and 2015 in Indonesia. Primary forest decreased by approximately 24.3%, with the most rapid degradation and deforestation occurring from 1996–2000, then 2003–2006, 2000–2003, 2006–2009, and 2009–2015 in order of decreasing pace. Of the 143 281 km^2 total decrease, 8763 km^2 occurred in Sumatra, and 31 653 km^2 occurred in Kalimantan, accounting for 16.9% and 24.8% of their primary forest area in 1990, respectively. Although secondary forest experienced over 80% (125 037 km^2) of primary forest conversions, this decreased by about 15.6% (82 524 km^2) from 1990–2015. Indonesia lost around 20% (227 039 km^2) of its natural forest (primary plus secondary forest) during this period, with the highest deforestation rate (2.11%, 29 746 km^2 yr^{-1}) occurring from 1996–2000, with 2006–2009 a distant second (1.00%, 9512 km^2 yr^{-1}), followed by 2003–2006 (0.85%, 8378 km^2 yr^{-1}) and 2012–2015 (0.73%, 6647 km^2 yr^{-1}). Figures 2(b) and (c) illustrate these LULC changes in Sumatra and Kalimantan, respectively. The two islands together represent the majority of areas of deforestation; around 65% (517 629 km^2) of deforestation in Indonesia during 1996–2000 occurred on these two islands, with the corresponding percentage jumping to 97% (408 017 km^2) in the period

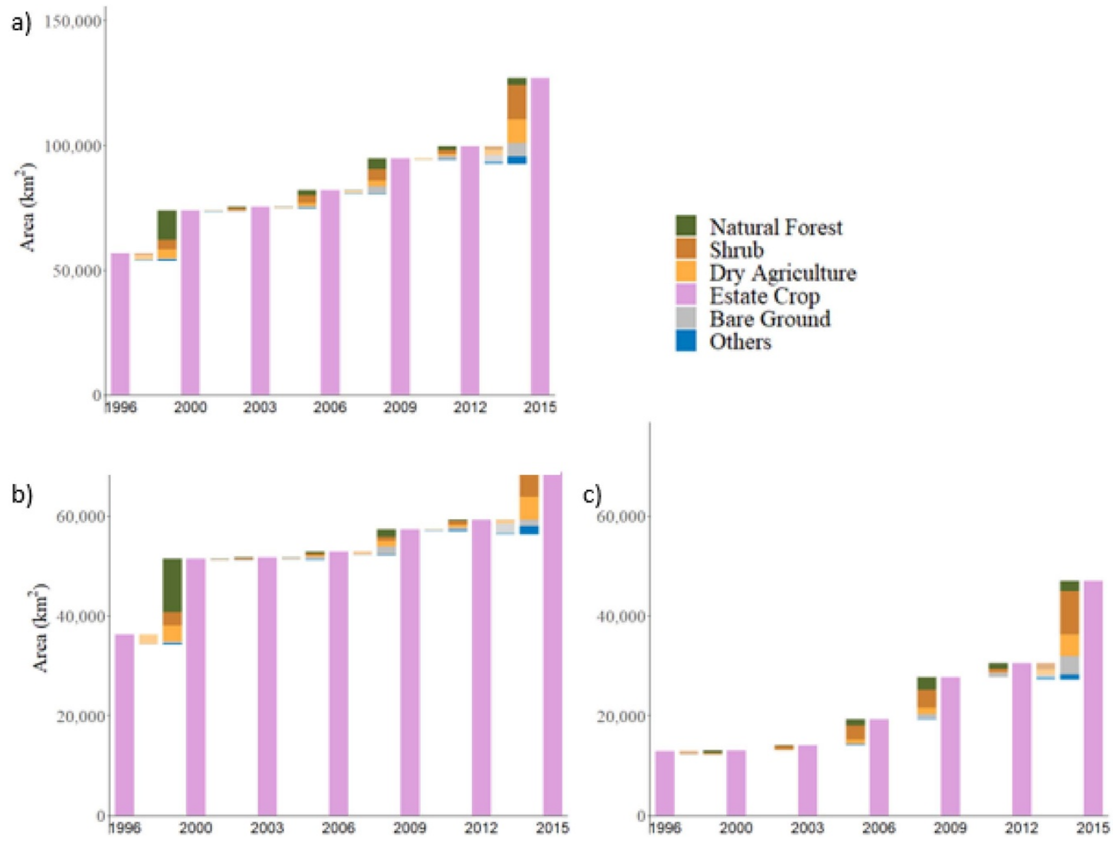


Figure 3. Direct conversions related to estate crops for the period 1996–2015. (a) Direct conversions related to estate crops for the whole country; (b) direct conversions related to estate crops in Sumatra; (c) direct conversions related to estate crops in Kalimantan. The area of estate crops for each year are denoted by the bars cross the axis, while the floating stacked bars depict the LULC changes within the six classes. The increments indicate the inflows from other classes to estate crops, and the decrements indicate the outflows from estate crops to other LULC classes. The inflows are significantly larger than the outflows.

2009–2012, and falling back to 85% (392 845 km^2) from 2012–2015. Sumatra lost 44.69% (90 206 km^2) of its natural forest in the period from 1990–2015 (figure 2(b)), accounting for 39.7% of country-wide deforestation, while 24.93% (87 907 km^2) natural forest disappeared in Kalimantan during the same period (figure 2(c)), accounting for 38.7% of the deforestation for the country as a whole. The deforestation rate in Sumatra was consistently higher than the country's average, with the highest annual rates occurring in the periods from 1996–2000 (5.36%, 12 514 km^2 yr^{-1}) and 2006–2009 (3.59%, 4876 km^2 yr^{-1}), in conjunction with the occurrence of El Nino events (1997 and 2006) (Field *et al* 2016). Although the deforestation rate was consistently high, and fluctuated, the total figure decreased as time went by, which is probably due to the long history of agriculture and plantations on the island (National Research Council 1993, Wicke *et al* 2008, Syuaib 2016), giving rise to the availability of suitable land for productive use which was no longer covered by natural forest (Austin *et al* 2017). The deforestation rates in Kalimantan were higher than the country's average after 2000, when industrial oil palm plantation was widely introduced to the island (USDA 2010).

Meanwhile, agriculture activity increased significantly (figure 2). The area for dry agriculture increased by the greatest amount, and estate crops experienced the most rapid expansion. Together with those areas degraded to shrub and bare ground, these were the major drivers of deforestation in Indonesia. Estate crop area increased from less than 45 000 km^2 to more than 120 000 km^2 (figure 2(a)), with an average annual speed of 4.24% (annual increase of 3277 km^2 yr^{-1}). The most rapid estate crop expansion occurred in the period 2012–2015 (with an average annual rate of 8.40%, or 9089 km^2 yr^{-1}), which was largely a result of the expansion occurring in Kalimantan (with an average annual rate of 15.47%, 5484 km^2 yr^{-1}), followed by that in 1996–2000 (6.77%, 5668 km^2 yr^{-1}), mainly driven by the expansion in Sumatra (9.14%, 5057 km^2 yr^{-1}). Sumatra and Kalimantan together accounted for around 97% of the estate crop expansion in Indonesia in the period from 1990–2015. Sumatra dominated the expansion prior to 2000, constituting 77.1% of the national expansion from 1990–2000 (28 877 km^2, figure 2(b)), while Kalimantan accounted for 63.67% of the national expansion after 2003 (51 645 km^2, figure 2(c)), driven by policy reforms in late 1990s which facilitated direct foreign investment in agriculture (Bissonnette 2015).

Natural forest, shrub, and dry agriculture are the three major direct LULC sources of estate crop expansion in Indonesia as a whole, as well as on the two islands specifically (figure 3). Shrub is the largest direct source of estate crop expansion in the country (figure 3(a)), with a contributing share of 32.66% (27 289 km^2), followed by natural forest (27.33%, 22 834 km^2) and dry agriculture (21.45%, 17 924 km^2). Natural forest was the largest direct source of estate crop expansion in Sumatra (figure 3(b)), with a share of 33.59% (13 259 km^2), whereas shrub contributed a higher share as time went by, and was the second largest source, with a share of 23.83% (9409 km^2). In Kalimantan (figure 3(c)), the trend is somewhat different, as shrub accounted for 42.48% (16 318 km^2) of all direct conversions to estate crop from 1996–2015, and was the largest source in the periods from 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 for both islands, particularly from 2012–2015 (see figures 3(b) and (c)). These shifting patterns of estate crop expansion are consistent with the findings of Austin *et al* (2017), who also reported a steadily declining rate of oil palm plantations displacing natural forest. This shifting pattern may be explained in the context of the following three reasons: (a) Conservation interventions by the government, NGOs and the private sector with respect to the oil palm industry (Koh and Butler 2009, Indonesian President Instruction no. 10 2011, Indonesian President Instruction no. 6 2013, Von Geibler 2013, United Nations 2014, Butler 2015, Barthel *et al* 2018) are making some progress towards natural forest protection, although an extension of this protection to cover secondary forest is also needed (Austin *et al* 2015, Sumarga and Hein 2016). (b) As the availability of suitable forestland becomes more limited, estate crop expansion tends to occur via the conversion of existing agricultural land (Meyfroidt *et al* 2014). (c) A smallholder requiring access to existing oil palm processing mills will tend to prefer low-biomass land (Walker 2004, Meyfroidt *et al* 2014).

Sizeable conversions are observed in relation to bare ground, particularly in Sumatra and Kalimantan in the period after 2000 (figures 2, 3 and S3). The major sources of bare ground establishment were secondary forest and shrub (figure S3). The clearance of natural forest to obtain bare ground made up a higher portion of deforestation as time went by on both islands (see figure S3). In the period from 1996–2015, bare ground accounted for 12.03% (4747 km^2) and 15.30% (4878 km^2) 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* 2012a), bare ground might be regarded as an intermediate phase of oil palm expansion.

3.2. Regression results

We first ran pooled regression models of oil palm expansion into the three major land sources in Indonesia during 1996–2015. The regression results, as shown in table 1, indicated that oil palm expansion in Indonesia tended to occur in regencies with longer access times 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 a more significant presence of estate crop plantation in 1990. Higher export value in the previous period ($t-1$) was positively and significantly associated with a greater prevalence of oil palm expansion, supporting the proposition that oil palm expansion in Indonesia was largely driven by its profitability in terms 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 will continue to expand into both natural forest and low-biomass land. This positive stimulation effect is stronger in relation to expansions into low-biomass LULC types, such as dry agriculture and shrub, than into natural forest. Numerically speaking, an increase of 1 billion (2000) USD in export value in the previous period promises an increase in 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 also ran spatial panel random effect models in the forms of spatial lag, spatial error and spatial Durbin. Figure 4 visually presents 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, and that 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 for 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,

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

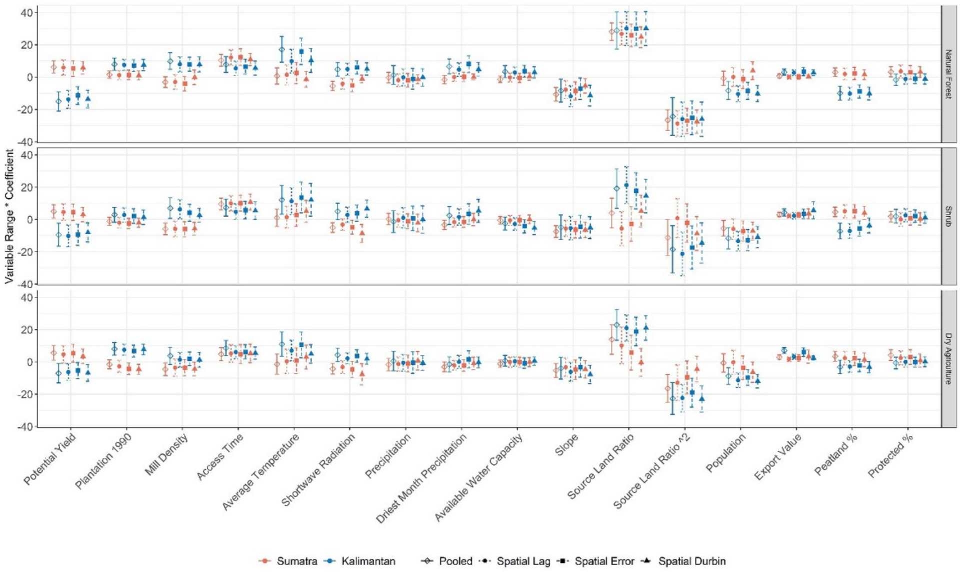
	Natural forest			Shrub			Dry agriculture		
	$\hat{\beta}$	t-value	sig.	$\hat{\beta}$	t-value	sig.	$\hat{\beta}$	t-value	sig.
(Intercept)	−114.400	−2.052	**	−77.669	−1.287		−43.563	−0.727	
Oil palm potential yield	0.015	1.542		0.034	3.246	***	0.039	3.661	****
Plantation in 1990	0.024	1.807	*	0.042	2.976	***	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	11 184.770			11 516.140			11 480.520		
Log likelihood	−5573.384			−5739.071			−5721.262		

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

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		

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



			Sumatra
Spatial lag	NF	φ	0.188***
		λ	0.184***
	Sh	φ	0.200***
		λ	0.221***
	DA	φ	0.240***
		λ	0.319***
Spatial error	NF	φ	0.183***
		ρ	0.193***
	Sh	φ	0.168**
		ρ	0.245***
	DA	φ	0.210***
		ρ	0.344***
Durbin	NF	φ	0.234***
		ρ	-0.553***
		λ	0.590***
	Sh	φ	0.136**
		ρ	0.646***
		λ	-0.513***
	DA	φ	0.202***
		ρ	0.756***
		λ	-0.647***
			Kalimantan
Spatial lag	NF	φ	1.00E-08
		λ	0.340***
	Sh	φ	0.018
		λ	0.343***
	DA	φ	1.00E-08
		λ	0.455***
Spatial error	NF	φ	1.00E-08
		ρ	0.373***
	Sh	φ	0.043
		ρ	0.382***
	DA	φ	1.00E-08
		ρ	0.442****
Durbin	NF	φ	1.00E-08
		ρ	0.032
		λ	0.318*
	Sh	φ	0.039
		ρ	0.690***
		λ	-0.487***
	DA	φ	1.00E-08
		ρ	-0.247***
		λ	0.598***

Figure 4. Spatial panel random effect model results for oil palm expansion in Sumatra and Kalimantan. Vertical pars correspond to 90% confidential intervals. The vertical axis (Variable Range × Coefficient) is the scaled coefficient, which can be used to render the coefficients comparable[5]. 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 significant levels of 10%, 5%, 1%, and 0.1%, respectively.

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 of the oil palm expansions. Meanwhile, the expansion into Kalimantan demonstrated a significant tendency to occur at areas with lower AWC when the spatial autocorrelations of the explanatory variables were addressed. The effects of spatial autocorrelations were larger in the dry agriculture models for both islands, and led to more significant changes in the explanatory variables in the models of Sumatra. When the spatial autocorrelations in Kalimantan were addressed, the coefficients for shortwave radiation became insignificant, while areas with gentler slopes were significantly preferred. For models of Sumatra, the expansion pattern is strongly associated with the significant positive spatial autocorrelation, with the exception that those areas with little estate crop plantation in 1990 were significantly preferred by oil palm expansion to dry agriculture, once the spatial autocorrelations between the explanatory variables were addressed.

Figure 4 indicates that oil palm expansion on the two islands also tended to occur in areas relatively remote from major cities, in contrast to the assumptions and results of some other researches (Pirker *et al* 2016, Sumarga and Hein 2016, Lim *et al* 2019). This result may be explained by the location choice sequence of plantation developers, which is similar to the pecking order sequence of corporate managers in considering their sources of financing (Myers and Majluf 1984, Vogt 1994). This means that suitable areas with better access to major cities were already occupied by existing plantations, so thath any new plantations must therefore be located in more remote areas 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 occurred earlier, and the expansion was also faster before 2000 in Sumatra than in Kalimantan, while the expansion pace grew more rapidly in Kalimantan after 2003 (figures 2(b) and (c); USDA 2013). Since Sumatra has a longer oil palm cultivation history and more intense agricultural activity (National Research Council 1993, Wicke *et al* 2008, Syuaib 2016), the natural forest resources remaining for estate crop plantation has become limited (figure 2(b)). Compared with Sumatra, Kalimantan was a comparative latecomer (Wicke *et al* 2008, Austin *et al* 2017), and land resources for oil palm expansion on the island were therefore less limited (figure 2(c)). Therefore, the expansion patterns of oil palm in Kalimantan proved to be better characterized by our explanatory models than those of Sumatra.

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

[5] To make the contributions of variables comparable, explanatory variables are scaled by range method: *variable range* $=$ variable$_{\max}$ $-$ variable$_{\min}$, $\text{Variable}_{\text{scaled}} = \frac{\text{Variable}}{\text{Variable Range}}$, $\text{Coef} \times \text{Variable} = \text{Coef}_{\text{scaled}} \times \text{Variable}_{\text{scaled}}$, therefore, $\text{Coef}_{\text{scaled}} = \text{Coef} \times \text{Variable Range}$.

Table 3. Results of pooled and spatial panel models of oil palm expansion in bare ground areas of 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 ratio^2	−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	***
R^2	0.373											
AIC	1478.492			1524.830			1518.596			1515.214		
Log likelihood	−721.246			−710.415			−707.298			−704.607		

Note: *, **, ***, and **** stand for significant levels of 10%, 5%, 1%, and 0.1%, respectively.

as well as with lower conversion cost. The stimulation effects of export value were statistically significant and positive for oil palm expansion into each of the three sources in Kalimantan, but not significant for the case of expansion into natural forest in Sumatra. Oil palm expansion in Kalimantan, particularly into natural forest, was more likely to occur in areas with more suitable climatic conditions, such as high shortwave radiation and higher precipitation in the driest month. In both the countrywide and Kalimantan models, oil palm expansion showed an inverted 'U'-shaped relationship with each of the source land ratios, indicating that oil palm expansion tended to occur in areas within the medium range of the source ratio (figure S2). These findings were consistent with those of existing research (Busch *et al* 2015, Euler *et al* 2017, Busch and Engelmann 2018). In contrast, on Sumatra island, such an inverted 'U' shape existed in the expansion into natural forest for all models, and into dry agriculture for the pooled model (figure S2). With regard to infrastructure and market factors, the expansion in Kalimantan tended to benefit from existing infrastructure, associated with existing plantations and processing mills, and the beneficial connection was more significant and stronger with expansion into natural forest. By contrast, the plantation in 1990 and mill density did not constrain oil palm expansion into any sources in Sumatra, since oil palm plantation and the associated infrastructure had already dispersed over the island, with the exception of the mountainous area along the west coast. Locations with lower population density were preferred for oil palm expansion into all three land sources in Kalimantan, which could be explained by the following factors: (a) oil palm was less labor intensive than alternative crops (Feintrenie *et al* 2010, Euler *et al* 2017, Gatto *et al* 2017), (b) locations with higher population densities and a longer history of planting traditional crops were less attractive for switching to oil palm (Gatto *et al* 2015), and (c) oil palm companies intended to avoid the land tenure conflicts and high transaction costs associated with consolidating land from smallholders (Meyfroidt *et al* 2014). Nevertheless, this relationship was significant in Sumatra for the expansion into shrub only. The percentage of peatland showed opposite effects in terms of oil palm expansion in Sumatra versus Kalimantan. The negative relationship in Kalimantan might be ascribed to the fact that oil palm establishments on the island preferred mineral land to peatland, either due to the lower cost of land preparation, or with the intention of reducing CO_2 emissions (Meyfroidt *et al* 2014, Afriyanti *et al* 2016, Rulli *et al* 2019).

In contrast to our expectations, the potential yield of oil palm showed a negative effect on oil palm expansion in Kalimantan, which could be explained by the location choice sequence of plantation developers, which is similar to the pecking order sequence of corporate managers in considering their sources of financing (Vogt 1994). Areas with higher potential yield of oil palm also offer greater potential yields for other types of plantation, such as dry agriculture crops and paddy fields; as such, those areas had already been occupied by existing agricultural activity and estate crop plantations. Interestingly, such pecking order effects were not found in Sumatra, which might be explained in terms of the following two reasons: Firstly, compared with Kalimantan, where all source lands are generally suitable for oil palm plantation, with a potential yield ranging between 43 and 71 ton ha^{-1}, the potential yield of oil palm in Sumatra ranges between 6 and 72 ton ha^{-1}, with regencies along the west coast being entirely unsuitable for oil palm plantation. Secondly, owing to its longer history of plantation (National Research Council 1993, Wicke *et al* 2008, Syuaib 2016), remaining land resources for new plantations in Sumatra have become limited since 1990 (figure 2(b)); as a result, oil palm has to expand into areas with relatively high potential yield, but which are very costly or illegal to convert, such as peatland and logging concessions (USDA 2010, Gaveau *et al* 2013, Austin *et al* 2017), and where the high proportion of smallholders (40%) aggravates the situation (Molenaar *et al* 2013, Meyfroidt *et al* 2014, Gatto *et al* 2015).

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

3.3. Bare ground as land banking for 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 in the first instance (see table 2). The results show that bare ground developed from natural forest was clustered in areas with large protected sectors, more natural forest cover, and were less significantly stimulated by the export value for the previous period, once spatial autocorrelations within the 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 to oil palm plantation was significantly stimulated by the export value for the previous period, and that conversion was clustered in those regencies with a higher proportion of protected areas. Considering that bare ground has been developed and converted to oil palm plantation at a rapid pace in recent years (Carlson *et al* 2012a, 2012b), the above results suggest that bare ground had been increasingly used as an indirect clearing-up tactic for 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 in any monitoring system, so that the system can more effectively track where and why bare ground is developed, and its eventual utilization. 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.

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, these expansions become more likely to occur in low-biomass areas, such as shrub and dry agriculture, than in 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, with the two islands hosting the majority of oil palm plantations 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 for most of the explanatory variables meet the theoretical expectations underlying the specification of our models. The results of our spatial panel regressions showed that oil palm expansion in Kalimantan was highly stimulated by the export value of oil palm products, took place in areas with better biophysical suitability and infrastructure accessibility, followed the pecking order sequence where more productive areas had already been occupied by existing agricultural activities and estate crop plantations, and avoided areas with high environmental values or socioeconomic costs.

However, as global demand for palm oil products continues to grow at a rapid pace, which in turn drives up its 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 areas with high conversion costs or legal barriers, including peatland and logging concessions. Under this highly plausible development scenario, future oil palm expansion in Indonesia would cause more environmental and social issues, such as increasing CO_2 emissions resulting from LULC conversion, the failure of land concessions, land right conflicts, etc. Therefore, to balance oil palm expansion and environmental conservation in Indonesia, current regulations, such as forest and peatland moratoriums, RSPO certification, protected areas, land use concessions, moratorium of new oil palm license issuance policy, and zero-deforestation commitments, should be continued, and extended to secondary forest and vulnerable ecosystems, as well as fully implemented and enforced. New policies and regulations on land banking are also urgently needed.

Data availability statement

All data supporting the findings of this study are included within the article (including any supplementary information files).

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