Spatial patterns and determinants of smallholder oil palm expansion over peatswamp forests in Riau

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Abstract

Tropcial peatswamp forests contain 20% of global carbon storage over the peatlands, while around 56% of tropical peatswamp forests occurred in Southeast Asia. But these forests were threatened by the rapid expansion of drainage-based agriculture and foresty. Consequently, from 1990 to 2010, the proportion of peat swamp forests in Southeast Asia declined from 77% to 36%. Meanwhile, the conversion of peatswamp forests to oil palm plantations has accelerated significantly during the last 3 decades, especially rising smallholder oil palms over peat soils due to their invisibility and difficulty in monitoring. However, existing studies either focus on the environmental impacts of peatswamp forests convertion into oil palm, or focus on few villages using survey data. We still lack an understanding of determinants and spatial distribution of smallholder oil palms expansion over peatswamp forests. In this study, we characterized the spatial distributions of land transitions from peatswamp forests in 1990 in Riau to land use and cover in 2019 from multiple socioeconomic and biophysical perspectives. In addition, we identified the relative influences of different factors on the land transitions from peatswamp forests to smallholder oil palms through spatial logit model. We found that small farmers prioritize the accessibility of land and oil palm mills, such as 95% of smallholder oil palms within 2km to roads and 26km to oil palm mills. With other variables constant, the mean likelihood of a given land area from peatswamp forest to smallholder oil palm significantly declined with rising distance to roads. Service roads developed by industrial oil palm plantations contributed to the expansion of both industrial and smallholder oil palm over peatswamp forests. Meanwhile, smallholder farmers are more likely to plant oil palm near residential roads and tracks for agriculture and forestry. Our findings could be used to identify strategies for protecting and managing those remaining peatswamp forests in Indonesia.

1. Introduction

Tropical peatlands represent 10-30% of all terrestrial carbon storage (Hodgkins,et al., 2018) and support some of the most biodiverse plant and animal communities on Earth (Posa, et al., 2011;Harrison, et al., 2018). Tropcial peatswamp forests contain 20% of global carbon storage over the peatlands(Cooper, et al., 2020), and approximately 56% of tropical peatlands occur in Southeast Asia (Page, et al., 2011), where they have formed due to the accumulation of plant debris beyond the extent of river floodwater and under rain-dependent conditions through thousands of years (Takada, et al., 2016).Tropical peatswamp forests provide a range of ecosystem services, such as provision of livelihoods through fishing, hunting, and non-timber forest products. However, these forests have been extensively logged for timber and subsequently drained for the development of tree crop plantations for forestry and agriculture (Koh, 2011; Cooper, et al, 2020). Between 1990 and 2010, the proportion of peat swamp forests in Southeast Asia declined from 77% to 36% (Miettinen et al. 2011). The conversion of tropical peatswamp forests to monoculture oil palm plantations has led to the loss of endemic biodiversity in these ecosystems (Giam, et al., 2012).Since large amount of oil palm production comes after forest and land fires (Adrianto, et al, 2020), which releases soil carbon to the atmosphere and has contributed 174 Mg C ha^{-1} to the growth of atmospheric CO2 (Guillaume, et al.,2018; Cooper et al.2020;Cooper et al.,2019).

Global demand for palm oil has been a major driver of land use change especially in Indonesia (Shigetomi, et al., 2020; Wicke, et al., 2011). Between 1990 and 2018, oil palm area in Indonesia increased from 1 million ha to 14 million ha, up by a factor of 13. During this period, oil palm cultivated under the smallholder sector increased from 0.3 million ha to 6 million ha while industrial plantation jumped from 0.5 million ha to 8 million ha, with the bulk of expansion occurring on the islands of Sumatra and Kalimantan (Indonesian side of Borneo) (Austin, et al., 2017).

According to the Indonesian Ministry of Forestry and the Environment, at least 3.4 million ha of oil palm area are situated in forested zones, established through a series of activities in forestry planning and managed by Ministry of Environment and Foresty, which are not legitimate for agriculture production without government permission (Safitri, et al., 2015; Enrici, et al., 2016) .Around 80% of these planted extents of oil palm in forested zones are in the provinces of Riau, South Sumatra, North Sumatra, and Central Kalimantan. Moreover, as global demand for palm oil keep increasing, unsustainable and less profitable land use practices have become more common, such as oil palm expansion from mineral soil to peat soil (Guillaume, et al., 2016). Meanwhile, the exhausting of existing farmland and the massive land uptake by the private sector also drove smallholders to enter illegal lands (forested zones) and marginal areas (Srinivas, et al., 2015; Schoneveld, et al. 2019).

Besides global demand and higher profitability, oil palm expansion could be also driven by a list of socioeconomic factors and policies, such as land rents, the establishment of oil palm mills, transportation infrastructure, concessions, and transmigration program (Lim et al., 2019; Xin, et al., 2021; Yackulic, et al.,2011; Euler et al.,2015; Gatto, et al.,2017; Agustira, et al., 2015;Geist, et al., 2002; Schonoveld, et al. 2019). Distance to mills and transportation networks are critical for oil palm plantations since fresh fruit bunch should be processed within 48 hours after harvests to assure the quality of crude palm oil (Corley, et al., 2008). Oil palm concession and transmigration programs provide land and labors for oil palm expansion in the beginning, especially for industrial plantations.

Oil palm concessions are the public lands that allocated to private companies by the government, and are also required to include local communities as plasma farms through oil palm production, such as training, supplies of seedlings and fertilizer, and buying oil palm fruits. But unclear land tenure and lack of transparency often caused conflicts between oil palm companies and local communities (Feintrenie, et al., 2010; Rist, et al., 2010).

Transmigration programs supported and accelerated the oil palm development in Indonesia, especially the smallholder oil palm (Widyatmoko, et al., 2019). For instance, the migration population in Riau province increased from 0.7 million in 1990 to 1.9 million in 2010 based on Indonesia Population Census (Supplement Fig.A1.). Moreover, migrant villages adopted oil palm earlier and faster compared to autochthonous villages (Gatto, et al., 2015).

Drivers and impacts of industrial oil palm plantations have been well documented, however, we still lack an understanding of the determinants and spatial patterns of smallholder oil palm expansion over peatswamp forests since 1990. Smallholder oil palms here refers to small plantations with heterogeneous shape, size, tree ages and less dense trail network, typically smaller than 25 ha (Descals, et al., 2021). In addition, oil palms used in this study refers to those with closed canopy while young plantations are classified as other land cover types. Our research aims to understand the spatial distribution and drivers of smallholder oil palm over peatswamp forests, and identify strategies to slow the deforestation over the remaining peatswamp forest. Therefore, we characterized the land transitions from peatswamp forests in 1990 in Riau to land cover in 2019 based on four types (smallholder oil palm, industrial oil palm, remaining peatswamp forests, and other land cover types) from socioeconomic and biophysical perspectives. We demonstrated whether significant differences exist between smallholder oil palm and industrial oil palm within and outside oil palm concessions. We developed spatial logit model to identify the major determinants of smallholder oil palms being the current land cover of peatswamp forests in 1990 in Riau. In this paper, we examined the impact of concessions, mill placement, transportation networks, population density and migration, and biophysical factors like precipitation, elevation, and slope. Our findings provide insightful implications for sustainable oil palm development in Indonesia and effectively protecting the remaining peatswamp forests. To the best of our knowledge, this study is among the first to characterize the spatial pattern of smallholder oil palms from socioeconomic perspectives and use spatial econometric modeling to analyze the determinants of smallholder oil palms expansion over peatswamp forest in Indonesia.

2. Method

2.1 Site description

In this study, we investigated the characteristics of the eventual land use for oil palm in 2019 over peatswamp forests (pristine and degraded) in Riau in 1990 , which decreased from 3.1 million ha (orange area and dark green area in Fig.1a; Miettinen et al., 2010) to around 0.98 million ha in 2015(dark green in Fig.1a; Miettinen et al., 2016). The current land-use for oil palm in 2019 does not indicate it is a direct or immediate driver of peatswamp deforestation since there could be intermediate land-uses in this 29-year period before the conversion to oil palm. We do not account for the dynamic and potential various land transitions from peatswamp forests in 1990 to oil palms in 2019. Although severe peatswamp deforestation occurred in Riau since 1990(Fig.1a), it is still the province with the second largest area of peatswamp forests in Indonesia. Given the vast importance of peat swamp forest in carbon storage and biodiversity, understanding drivers of peatswamp deforestation is important.

Oil palm expansion is one of the major drivers for deforestation over peatland in Riau (Adrianto, et al., 2020;Taheripour, et al., 2019). Riau is the largest producing province of palm oil production in Indonesia. Smallholder oil palm area in Indonesia increased from 0.3million ha in 1990 to 5.8million ha in 2018 (Tree Crops Estate Statistics of Indonesia 2018-2020). Riau accounts for 41% of national oil palm area and 36% of national palm oil production in 2018. Industrial and smallholder oil palm expansion both encroached into peat swamp forest in Riau (as shown in Fig.1b).

For the peat swamp forest area in 1990, 22.5% were allocated to oil palm concessions while 35.6% were allocated to wood and fiber concessions (Fig.3c). In addition, according to village potential survey data, some villages are dominated by migrants (Fig.4c).

In Riau, both temperature and precipitation are relatively high over peatland area in Riau. Between 1970 and 2000, the annual average temperature in Riau measured from 26.07 ℃ to 26.87℃. And the annual average precipitation over peatland area of Riau was 2447mm with range from 2166mm to 3265mm. In addition, the peatland area in Riau is relatively flat, with average slope 2.04 degree (0-25.47), and elevation 24.5m (-13m-116m).

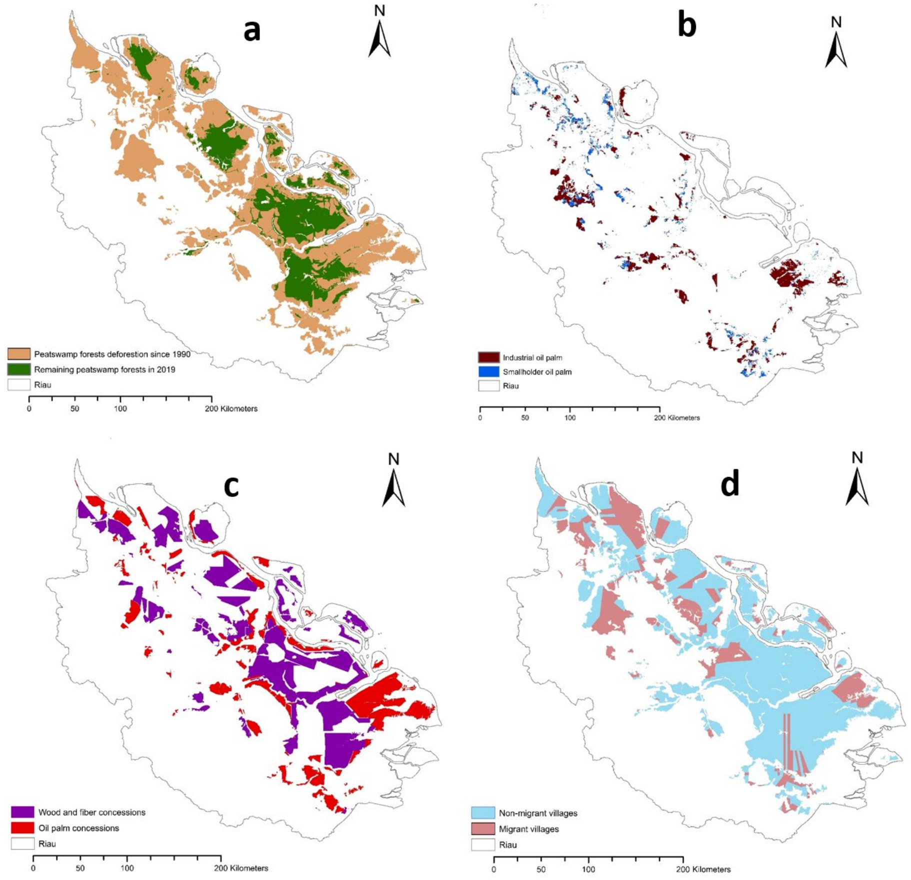

Fig.1 Peat swamp forest area, oil palm distribution, concessions and migrant villages in Riau. Panel a shows the peatswamp deforestation since 1990 (orange) and remaining peatswamp forests in 2019 (dark green) in Riau. Panel b shows the industrial (dark red) and smallholder (blue) oil palm distribution over peat swamp forest area in 1990. Panel c shows the oil palm (red) and wood fiber (purple) concession over the land covered by peatswamp forests in 1990 in Riau. Panel d shows the areas belonging to migrant villages and non-migrant villages in 2018 over the land area covered by the peatswamp forests in 1990.

2.2 Data description

The map for smallholder and industrial oil palms with closed canopy in2019 are from Descals, et al. (2021). Smallholder and industrial oil palm plantations are usually different from shape, size, tree ages, density of trail, road/canal network. Compared to industrial oil palm plantations, smallholder plantations tend to less structured in shape, more heterogeneous in tree ages, and less dense in trail and road network. Moreover, the map could not distinguish between types of smallholdings (independent, scheme). In addition, the user's accuracy of the map in industrial and smallholders was 88.22 ± 2.73 % and 76.56 ± 4.53 %, and the producer's accuracy was 75.78 ± 3.55 % and 86.92 ± 5.12 %, respectively. The map for peatswamp forest in 1990 is based on the peatland cover map from Centre for Remote Imaging Sensing & Processing (CRISP), and Miettinen(2010). The map for peatswamp forest in 2019 is from WebGIS Kementerian Lingkungan Hidup Dan Kehutanan(KLHK) OpenSource. We extracted the peatswamp forests (including pristine and degraded) in Riau from peatland cover map in 1990, and the peatswamp forests(including pristine and degraded) from 2019 land cover map. Then we overlay the 1990 peatswamp forest with the map for smallholder and industrial oil palms in 2019 and the map for remaining peatswamp forests in 2019. Therefore, we have four land use types in 2019 for peatswamp forest in 1990, including smallholder oil palm, industrial oil palm, remaining peatswamp forest, and other land uses.

The list and spatial locations of oil palm mills are from Center for International Forest Research (CIFOR). The researchers of CIFOR compiled the list of oil palm mills from supply chain document on traceability report of major palm oil processor in Indonesia (Musim Mas, GAR, Asian Agri, and Wilmar) and verified the spatial locations using Google Earth imagery or other available high resolution images. We compared this list with the Universal Mill List (World Resources Institute, 2018), and found the former has more data about Riau oil palm mills. Based on the spatial location of oil palm mills, we calculate the Euclidean distance from each pixel to the nearest oil palm mills.

The polyline maps of roads and waterways are from Humanitarian Data Exchange (HDX), produced by Humananitian OpenStreetMap team, which is updated in 2020. The road map distinguishes roads by function and importance, and covers any kind of road, street, path within the road network, such as highway (primary, secondary, tertiary), residential roads(connecting houses), service roads(within industrial estates, parks, etc), tracks (mostly for agricultural or forestry use) . The waterways are distinguished by the types of flows (free flow, pipe flow), and the ways it was produced (man made, natural), such as canal, drain, ditch, river, stream. Based on roads and waterways map, we calculated the Euclidean distance of each pixel to the nearest roads and the nearest waterways. Travel time to major cities was from a new travel time map developed by the European Commission and the World Bank in 2015, which was based on Nelson (2008). The travel time to cities with populations larger than 50 000 using land- or water-based means of travel and a cost-distance algorithm is publicly available as 30 arc-second.

Population density data was collected from LandScan Global 2019(Dobson, et al., 2000), which provides an ambient (average over 24 h) population distribution at the approximately 1 km (30″ X

30″) spatial resolution. This database is updated annually, and has been widely used in the previous studies (Linard, et al., 2011; Tateishi, et al., 2011).

Precipitation and temperature data are based on historical data for 1970-2000 from WorldClim data website. We collected annual precipitation, precipitation of driest quarter, and annual mean temperature at 30 seconds (~1 km^2) resolution for our study area. The terrain data, including elevation and slope were compiled from the Shuttle Radar Topography Mission (NASA, 2009), which is at 3 arc-second (approximately 90 m) resolution.

The potential yield of oil palm was collected from GAEZ v3.0, which was developed by The International Institute for Applied Systems Analysis (IIASA) and the Food and Agriculture Organization of the United Nations (FAO) to assess the potential productivity of land under different management regimes. Considering smallholder oil palm productions are also market oriented and have high fertilizer input levels like industrial plantations (Woittiez,et al., 2018; Darras, et al.,2019), we used the potential yield of palm oil with high inputs level under rain-fed over the historical period 1961-1990. However, smallholder oil palm farms tend to have lower production due to poor access to the best seedlings and fertilizers, especially outside of concessions.

Since migrants may have different preference for oil palm and could adopt earlier and faster (Gatto, et al., 2015), we used a dummy variable about migrant village to represent the impacts of migrant villages on smallholder oil palm expansion over peat swamp forest. Based on village potential survey in 2018, a village community with majority tribe/ethnic Jawa is treated as migrant villages, otherwise, non-migrant villages.

Table 1 Response and predictor variables used in the analysis

Variable	Description	Source	Spatial resolution	Temporal resolution
Response variables				
Smallholder oil palm (OP_SH)	Presence or absence of smallholder oil palm	Descals,et al (2020)	10m*10m	2019
Industrial oil palm(OP_IND)	Presence or absence of industrial oil palm	Descals, et al(2020)	10m*10m	2019
Predictor variables				
Economic factors(E)				
Distance to oil palm mills(km)	Grid cell distance to nearest oil palm mills	CIFOR(2017)	Polygon	2017
Distance to roads(km)	Grid cell distance to nearest roads	Humanitarian Data Exchange(2020)	Polyline	2020
Distance to waterways(km)	Grid cell distance to nearest roads	Humanitarian Data Exchange(2020)	Polyline	2020
Travel time to cities(h)	Grid cell travel time to nearest cities with population > 50k	Nelson,A.,(2008)	1km*1km	2015
Biophysical factors(B)				
Precipitation I(cm)	Annual precipitation	Worldclim.org	1km*1km	1970-2000
Precipitation II (cm)	Precipitation of driest quarter	Worldclim.org	1km*1km	1970-2000
Temperature(℃)	Annual mean temperature	Worldclim.org	1km*1km	1970-2000

Slope(degree)	Gridded slope based on elevation	SRTM(NASA,2009)	90m*90m	2009
Elevation(m)	Gridded elevation	SRTM(NASA,2009)	90m*90m	2009
Potential yield(t/ha)	Potential yield with intermediate inputs	IIASA(2018)	10km*10km	1961-1990
Concession factor(C)				
Oil palm concession dummy(C1)	Grid cell value =1 if inside oil palm concession, otherwise 0	WRI(2019)	Polygon	2019
Wood fiber concession dummy(C2)	Grid cell value=0 if inside wood fiber concession, otherwise 0	WRI(2019)	Polygon	2019
Social factors(S)				
Population density(persons/km^2)	Population count per km^2	LandSCAN(2019)	1km*1km	2019
Migrant village dummy	Grid cell value =1 if the first ethnicity is Jawa in the village, otherwise 0	PODES (2018)	Polygon	2018

2.3. Spatial logistic regression model

We used a logistic regression model to estimate the probability that the current land cover of peatswamp forests in 1990 is mature smallholder oil palms. The dependent variable in logistic regression is a binary response variable *OP_SH* (1=presence of mature smallholder oil palm, 0= absence of mature smallholder oil palm), which is related to a set of predictor variables, including biophysical factors, socioeconomic factors and industrial plantations. The logistic function is as follows.

$$P = E(OP\_SH) = \frac{\exp(\mathrm{X_i}; \gamma)}{1 + \exp(\mathrm{X_i}; \gamma)}$$

Where P is the probability of peat swamp forest converted into smallholder oil palm, *E* (*OP_SH*) is the expected value of the dependent variable *OP_SH*. X_i is a vector of variables listed in Table 1 and γ is a vector of coefficients for each variable.

We first estimate the non-spatial logit model to explain the effects of biophysical and socioeconomic drivers on smallholder oil palm expansion over peat swamp forest, and check the spatial autocorrelation with Moran's I test. Model selection is based on AIC comparison of different model specifications. To address the issue of spatial autocorrelation, we include a spatial autocovariate term in the model, which is calculated using spdep and lattice packages in R based on the method described in Bardoe et al. (2015). Considering the rarity of smallholder oil palm expansion over the peatswamp forest, the expansion regression was fit using a weighted loss function. A weight variable was calculated by summing all smallholder oil palm pixels (S1) and all non-smallholder oil palm pixels(S2). Non-smallholder oil palm pixels were assigned as a weight of S1/(S1+S2) while smallholder pixels were assigned a weight of S2/(S1+S2). Model parameters and accuracy were estimated using 10-fold cross validation for spatial binomial logit model. Robust standard errors were calculated using White's estimator via the foreign and sandwich packages in R.

3. Results

3.1 Distribution of smallholder oil palm and other land cover types

In 2019, 15% of peatswamp forests in 1990 in Riau was covered by oil palm (10% for industrial oil palm and 5% for smallholder oil palm), 55% by other trees and crops, and 30% remained as peatswamp forest (Fig.2a). Oil palm might be not the direct cause for peatswamp deforestation, but we could identify the spatial preference for smallholder farmers based on the current spatial distribution of smallholder oil palm.

Oil palm and wood fiber concessions in Riau have been incompletely planted although more than half area of peat swamp forest in 1990 was allocated to different concessions. Some companies may keep the area with high conservation value or high carbon stock within their concessions (Smith, 2020).Within oil palm concessions, only 30% are industrial oil palms and 6% are smallholder oil palms. And 5% of oil palm concessions are remaining peat swamp forest. Within wood and fiber concessions, 1% are industrial oil palms and 2% are smallholder oil palms while 26% are remaining peat swamp forest.

Smallholder oil palm area is more located outside the oil palm concession while the majority of industrial oil palms are located within oil palm concession (Fig.2b). Moreover, oil palm also expanded into wood and fiber concessions in Riau. 14% of smallholder oil palm area is within wood and fiber concession, while only 5% for industrial oil palm (Fig.2d).

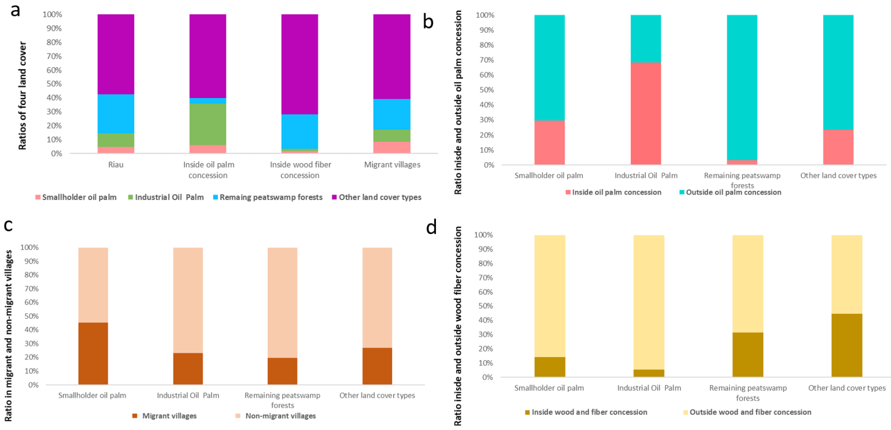

Fig.2 Distribution of four land types from 1990 peat swamp forest in Riau. Panel a shows ratios of four land cover types from Riau peatswamp forest in 1990, inside oil palm concessions, inside wood fiber concessions, in migrant villages. Panel b shows the ratio inside and outside oil palm concession for each land cover type. Panel c shows the ratio in migrant and non-migrant villages for each land cover type. Panel d shows the ratio inside and outside wood and fiber concession for each land cover type.

Oil palm plantations are usually spread surrounding oil palm mills for rapid processing after harvesting to make sure the quality of crude palm oil. However, distance to oil palm mills is significantly higher for smallholder than industrial oil palm, especially within oil palm concession. Industrial oil palm expansion over peat swamp forest in Riau since 1990 are within average distance 9km to the nearest mills, while smallholder oil palms are averagely 12km far from the nearest mills. This increased the marketing and transportation cost of oil palm fresh fruit bunch for smallholder farmers (Lee, et al., 2014).

Among different land cover types over peatland, smallholder oil palm is the closest to the roads, waterways and big cities (Fig.3b). Smallholder oil palms are located within average distance of 700 m to the nearest roads, 75% within 924m, and 95% within 2km. Moreover, for any given value of distance to roads within 1km, smallholder oil palms have the highest frequency among different land covers (Fig.S2). In comparison, industrial oil palms are averagely within 1305m to the nearest roads, 75% within 2km, and 95% within 4km. Moreover, smallholder oil palm areas are within average distance 5.5km to waterways and within average 6h to big cities (Fig.3c and 3d).

In addition, smallholder oil palms are distinct from industrial oil palms in terms of types of the nearest roads (Fig. 4). The nearest roads for 77% of industrial oil palm are service roads, which are for access roads to or within an industrial estate, while 40% of smallholder oil palms have service roads as the nearest roads (Fig.4a and 4b). This may indicate service roads developed by oil palm concessions contributed to both industrial and smallholder oil palm expansion. Moreover, 27% of smallholder oil palms have residential roads (roads connecting houses) as the nearest roads, 10% for tracks (roads for mostly agricultural or forestry uses). It is convenient and cost effective for smallholder farmers to plant oil palm close to where they live.

Moreover, compared with other land cover types, smallholder oil palm trees are more like to be located within those migration villages. In 2019, 45% of smallholder oil palms in Riau over land covered by peatswamp forests in 1990 in Riau occurred within migration villages while it is only 23% of industrial oil palm (Fig.2c). Last, with respect to biophysical factors, smallholder oil palms are more likely to locate in those regions with higher precipitation in the driest quarter and relative higher slope(Fig.3e, Fig.3h).

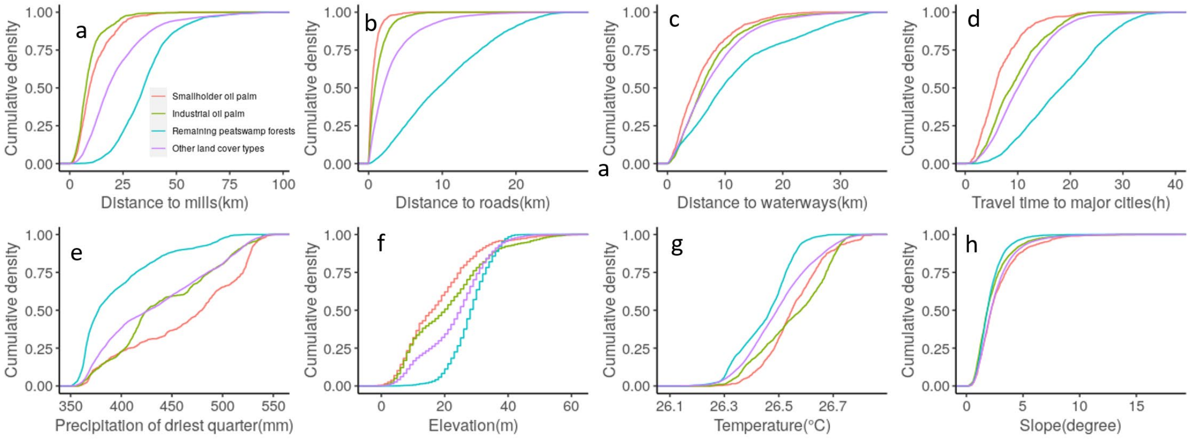

Fig.3 Spatial patterns and distribution of four land cover types. Panel a-d are distances to mills, roads, waterways, and major cities. Panel e-h are distribution of biophysical factors for four land cover types.

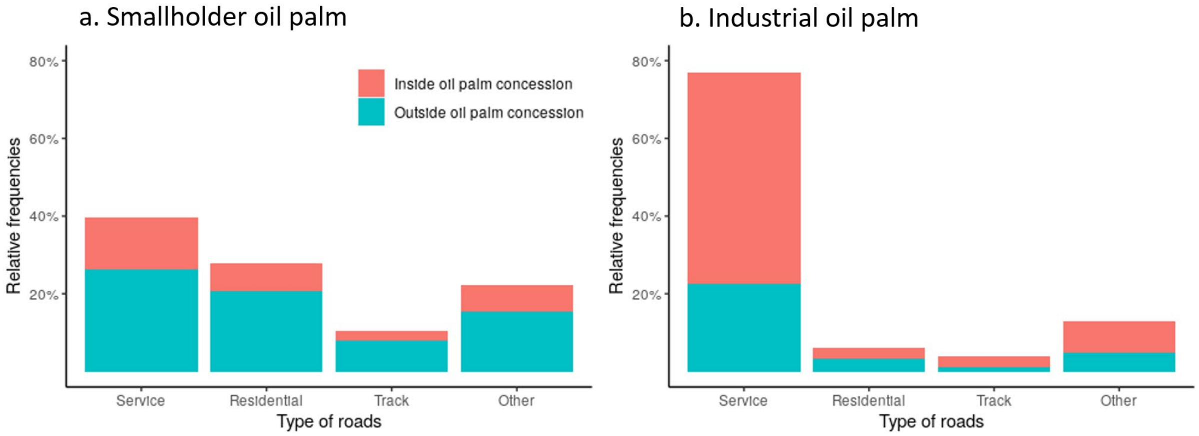

Fig.4 Frequency of types of nearest roads for smallholder and industrial oil palms. Panel a. Frequency of types of the nearest roads of smallholder oil palm inside and outside oil palm concessions. Panel b. Frequency of types of the nearest roads of industrial oil palm inside and outside oil palm concessions. For different types of roads, the definitions are as the following from https://wiki.openstreetmap.org/wiki/Key:highway. Service stands for access roads to, or within an industrial estate, camp site, business park, car park, alleys, etc. Residential stands for "roads which serve as an access to housing, without function of connecting settlements". Track represents roads for mostly agricultural or forestry uses. Other roads include primary, secondary, tertiary and unclassified highways, trunk, path, construction roads, etc.

3.2 Drivers of smallholder oil palm expansion over the peat swamp forest

Distance to mills adversely affect the expansion of smallholder oil palm. Outside the oil palm concession area, the odds of a given peat forest area being converted to smallholder oil palm increased by 6% (odd ratios=0.94, 95% CI [0.93, 0.96]) for every kilometer decrease in distance to the nearest mills. Holding all the other variables constant, the mean likelihood of peatswamp forest conversion into smallholder oil palm outside oil palm concessions decreases with rising distance to mills while the likelihood is really flat inside oil palm concessions (Fig.5a). Smallholder oil palm within oil palm concessions might be scheme smallholders who have their own network of transportation to bring FFB to mills and have guaranteed access to mills since they are contractually bound to companies.

Easy accessibility of land through road network plays a decisive role in smallholder oil palm expansion over peatland both within and outside oil palm concessions. The odds of a given land area being converted to smallholder oil palm outside concession area increased by 55% (odd ratios=0.45, 95% CI [0.38, 0.52]) for every kilometer decrease in distance to the nearest roads. Holding all other variables constant, land area outside oil palm concessions within 1km to the nearest roads has more than 50% of conversion into smallholder oil palm, on average (Fig.5b).

Concession areas may have limitations and constraints for the expansion of smallholder oil palm. The odds of a given peat forest area being converted into smallholder oil palm within oil palm concessions are about 71%(odd ratios =0.29, 95% CI [0.15, 0.56]) lower than the odds for outside oil palm concessions. The odds of being smallholder oil palm within wood fiber concessions are about 51% (odd ratios =0.49, 95% CI [0.33, 0.66]) lower than the odds for outside wood and fiber concessions.

Moreover, peatswamp forests in migration villages have higher likelihood to be converted into smallholder oil palm. The odds of a given peat forest area being converted to smallholder oil palm within migration villages are about 78%(odd ratios =1.78, 95% CI [1.34, 2.37]) higher than the odds for non-migration villages. However, these results do not mean that smallholder oil palms are planted and owned by migrants, even if the primary reason for migrants moving from other places to Riau is to plant oil palm (Budidarsono, et al., 2013). Schoneveld et al. (2019) found that indigenous groups are more likely to conduct land conversion into smallholder oil palms. Our modelling results only demonstrate the likelihood being converted into smallholder oil palm of peatswamp forests in migrant villages could be higher, which may related to the unclear land rights and boundaries.

Biophysical variables, including precipitation, elevation, slope, also have significant influence on the expansion of smallholder oil palm over peat. Smallholder oil palms are more likely planted in the regions with high precipitation, low elevation. The odds of a given peat forest area being converted into smallholder oil palm rises by 2% (odd ratios =1.02, 95% CI [1.01, 1.03]) with 1mm increase in precipitation of the driest month, and climbs 2% (odd ratios =0.98, 95% CI [0.96, 0.99]) with one meter drop in elevation.

However, population density and potential yield have no significant impact on the smallholder oil palm expansion over peatland. There are different from our hypotheses that smallholder oil palm farmers prefer regions with high potential yields and that regions with higher population density could have higher probability to convert peat forest into smallholder oil palms. Combining with the significant of distance to roads and mills, results indicate that small farmers prioritize the accessibility of land rather than potential yield.

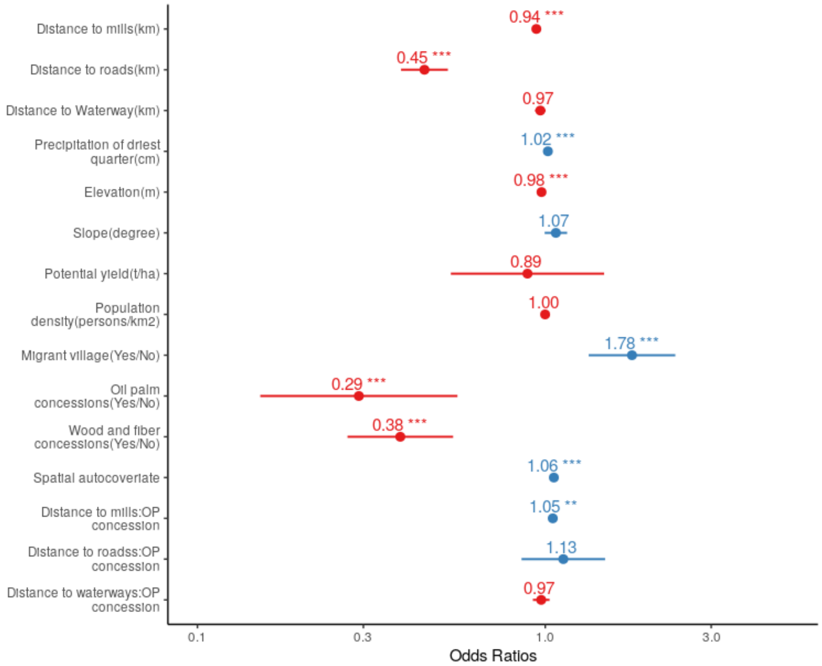

Fig.4 Relative influences of socioeconomic and biophysical variables on smallholder oil palm expansion over peat swamp forest in Riau. The variables with blue color means positive influences while red color reflects the negative impacts.

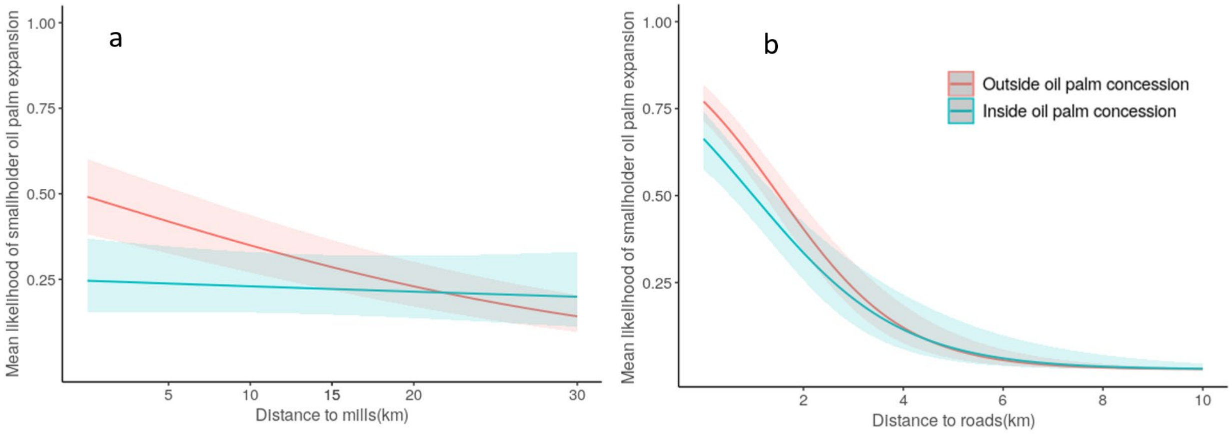

Fig.5 Partial dependence plots for distance to mills and distance to roads. Panel a. the mean likelihood of being smallholder oil palm changing with distance to mills. Panel b. the mean likelihood of being smallholder oil palm changing with distance to roads.

3.3 Regions with high risk of deforestation by smallholders

Considering 95% of current smallholder oil palm within 2km to roads and 26km to mills, we show where the remaining peat swamp forests in Riau are within these same ranges in Fig.6. These high risk areas that are located within migration villages are more likely to be converted by smallholder farmers. In addition, remaining peat swamp forest areas within oil palm and wood fiber concessions are also at high risk of deforestation due to no legal hindrance.

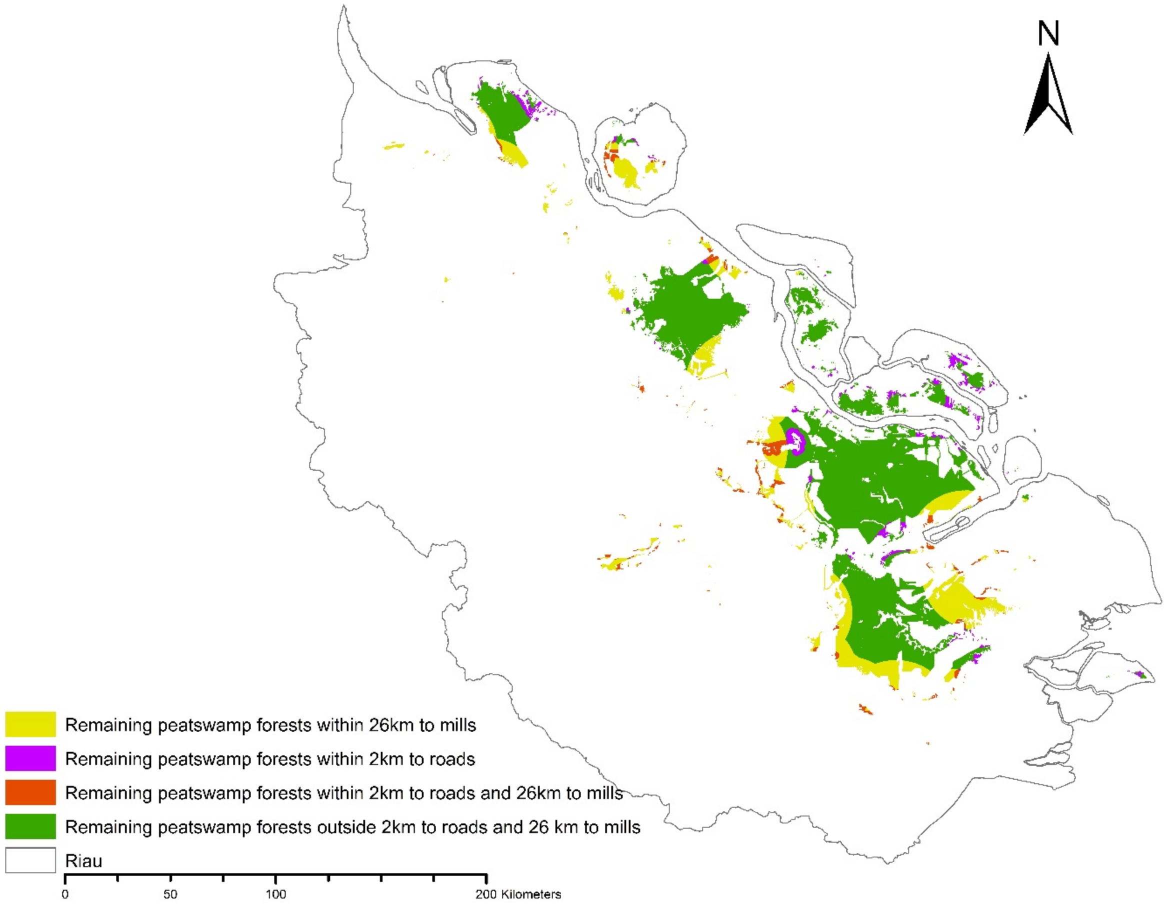

Fig.6 High risk area of remaining peatswamp forests in 2019 based on distance to mills and roads

4. Discussion

4.1 The role of roads and mills in smallholder oil palm expansion

Our results confirm the recognition that smallholder oil palm increased dramatically in the regions near to mills and roads (Cramb et al., 2013). But we identity that more than 90% of smallholder oil palms are close to one of four types of roads and demonstrate that short distance to roads is one of the most important drivers for smallholder oil palm expansion. Easy access to roads is important for smallholder oil palm farmers since some major management practices, such as harvesting and processing of fresh fruit bunches, could lessen as the distance to roads increases (Obiechina, 1985). Therefore, smallholder farmers prefer to plant oil palm in the areas near to roads, which could reduce the marketing cost and facilitate the harvesting and processing of fresh fruit bunches.

Distance to mills could be different for marketing and transportation costs, production costs (if inputs also distributed from mills area to other places), and even yields (Lee et al., 2013; Soliman et al., 2016). Then smallholder farmers that are far from mills would have less profits compared to industrial oil palm plantations, thereby possibly expanding more over forest area.

4.2 Implications for mitigating deforestation on peatland by smallholder

Given the critical role of road in the smallholder expansion, the design of future expansion of road network need to consider restricting road development in the surrounding of remaining peat swamp forest (e.g.,> 3 km from the remaining peat swamp forest). We identified that smallholder oil palms usually distributed along service roads, residential roads, unclassified highway, and track for agriculture and forestry. Therefore, restricting these types of roads could effectively render the expansion of smallholder oil palm over remaining peatswamp forest.

Building some mills close to smallholder oil palms may also contribute to mitigate the deforestation over peatland by smallholder. Close to mills could reduce the transportation costs to mills, which could directly improve profits and income of smallholder farmers, and may indirectly slow the deforestation by smallholders.

We identified the region with high risk of deforestation, which needs be prioritized for protection measures, such as Gaung Anak Serka district in Indragiri Hilir, Dayun district in Siak ,Rangsang in Kepulauan Meranti , Rupat in Bengkalis, and Sinaboi district in Rokan Hilir.

In addition, 31% of remaining peat swamp forest in Riau is within wood and fiber concessions while 3% are within oil palm concessions. The sustainability tradeoffs between the ecological values and economic returns from concessions should be reevaluated by the government as well as private companies. Remaining peat swamp forest inside concessions are excellent target for conservation (Nomura, et al., 2019).

4.3 Implication for the design of migration programs.

Transmigration programs were designed to reduce the rural poverty, however, careful planning and evaluation are required for oil palm expansion over forest area (Santika, et al.,2019). Gatto et al.(2015) found that transmigration programs in 1980s and 1990s play a key role in the start and spread of oil palm in Jambi. However, migrants and indigenous people are both likely to convert forestland into oil palm, and the radical reason could be unclear land ownerships and boundary of forest zones in migrant villages. Since transmigration program was restarted in 2015 in multiple provinces, land area for transmigrant villages should be allocated to the regions that are far from peat swamp forest area and implement good peatswamp forest planning, such as forest designation, delineation of boundaries and enactment (Safitri, et al., 2015).

4.4 Uncertainties and limitations

First, the user and producer accuracy of oil palm in Sumatra are lower than other regions with smallholder UA = 63.27 ± 7.82 % and industrial PA = 69.15 ± 4.62 %. This is mostly caused by classifying industrial oil palm as smallholder oil palm in Descals, et al.(2021), which restricted the farm size of smallholder oil palm within 25 ha following the official requirements of Indonesian government for smallholder oil palm. However, according to Jelsma et al. (2017), some independent smallholder oil farms could be larger than 200 ha, but still much smaller than a typical size of industrial oil palm estate. Moreover, the commission error for smallholder oil palm and omission error for industrial oil palm could be mostly caused by those smallholder oil palms with farm sizes greater than 25. If we relaxed the restrictions of smallholder farm size, the user accuracy for smallholder and producer accuracy could be both much higher. In addition, these commission and omission errors are not related to the key variables that we are of interests, and therefore would not affect our results.

Second, mills locations data are mainly collected from the supply chain reports of major companies which may not include all the palm oil mills, especially those small ones and outside oil palm concessions. However, our findings could still well reflect the impacts of proximity to oil palm mills on the expansion of smallholder oil palm over peatswamp forest area since 1990.

5. Conclusions

First, spatial patterns of smallholder oil palms are significantly different from other land cover types. Compared to industrial oil palm, remaining peatswamp forests, and other land cover types, smallholder oil palms are averagely the most closest to roads, waterway, major cities, and have higher precipitation in the driest quarter and higher slope, on average. For any given distance to road with 1km, smallholder oil palms have the highest frequency.

Moreover, smallholder and industrial oil palms are different from several perspectives. First, industrial oil palms are much closer to oil palm mills than smallholder oil palm, which could lead to different prices of fresh fruit bunch, and profits. Second, smallholder oil palms are more close to roads compared with industrial oil palms. Third, the majority of industrial oil palms are distributed along service roads that are for access or within industrial oil palm plantations, while the nearest roads of smallholder oil palms include service roads, residential roads for connecting houses, and tracks for agriculture and forestry.

Land transition from peatswamp forests in 1990 to smallholder oil palms is most driven by socioeconomic factors, such as distance to mills and roads, and transmigration programs, but constrained by oil palm concessions and wood fiber concessions. Population density and potential yield did not show significant impacts on the expansion of smallholder oil palm expansion. Among biophysical factors, precipitation of the driest quarter is the most important driver of smallholder oil palm expansion.

Further we could improve our current findings in the future research if we could obtain time series of land cover change over peatswamp forests, peat depth maps, maps shows the locations of oil palm mills with establishment date and capacity, as well as the land tenure and legal status for agriculture production.

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Supplementary Figures

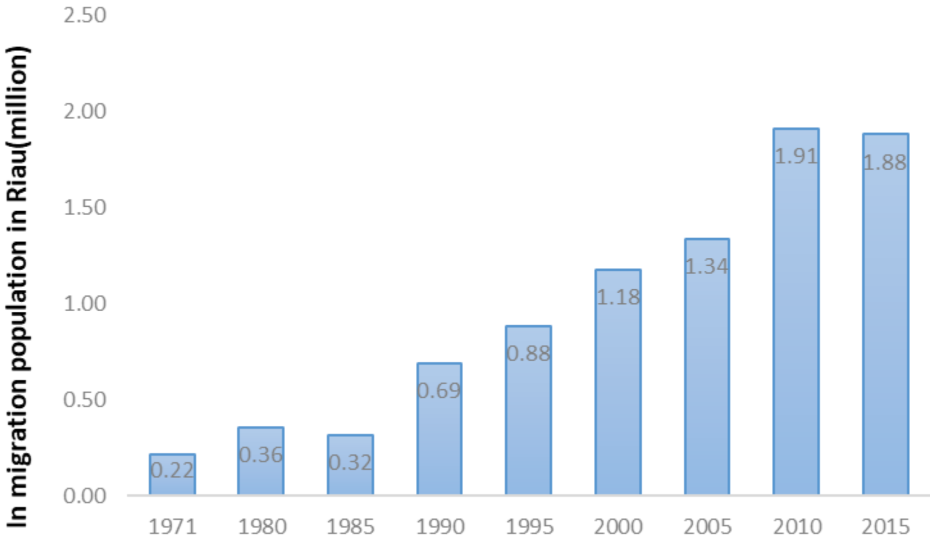

Fig.S1 In migration population in Riau

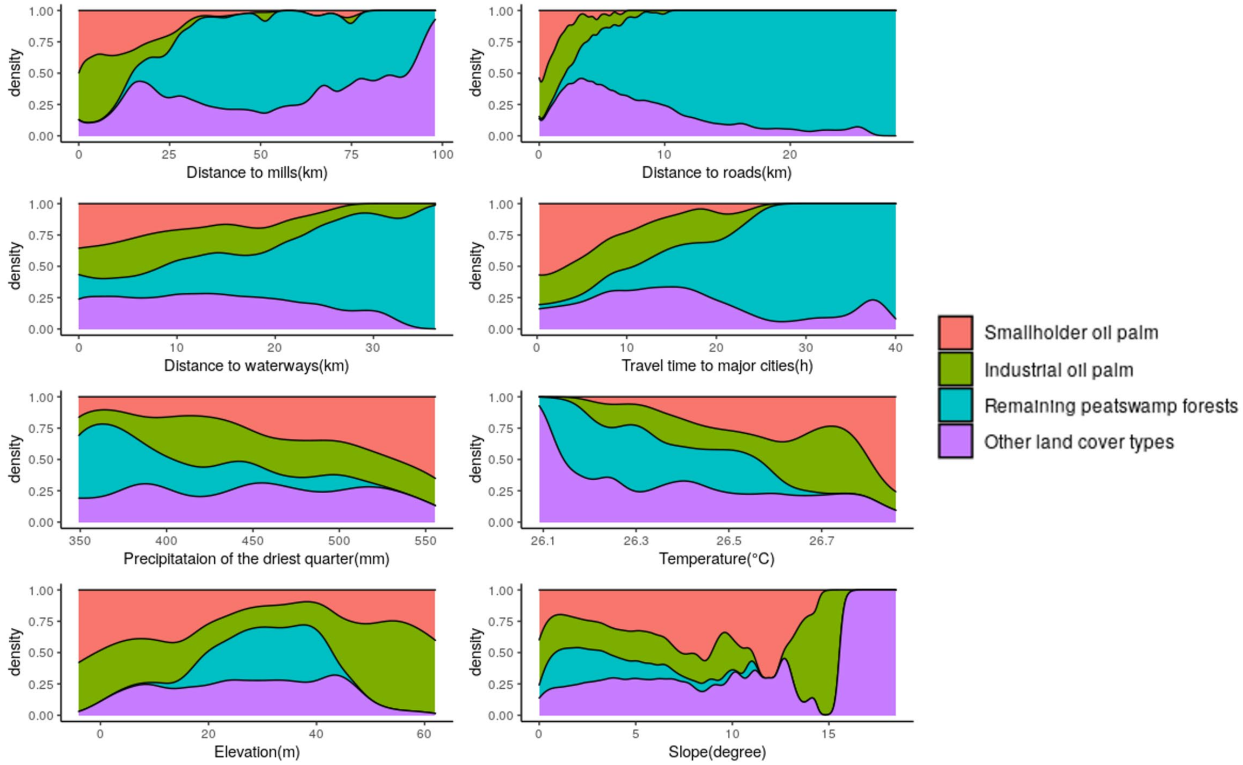

Fig.S2 Stacked density plots of four land cover types by different socioeconomic and biophysical factors