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Spatial patterns and drivers of smallholder oil palm expansion within peat swamp forests of Riau, Indonesia

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E-mail: xin.zhang@umces.edu and mark.cochrane@umces.edu**Keywords:** smallholder oil palms, peat swamp forests, spatial patterns, socioeconomic, biophysical, expansion, conservationSupplementary material for this article is available [online](#)

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**Abstract**

Protecting the tropical peat swamp forests in Southeast Asia is critical for addressing global sustainability challenges such as climate change and biodiversity loss. However, more than half of these forests have been lost since 1990 due to the rapid expansion of drainage-based agriculture and forestry. Within the oil palm sector, the number of regional smallholder oil palm plantings on peat soils has risen quickly. These activities are challenging to govern and manage, due to their fragmented nature and the numerous farmers involved. It is imperative to understand the spatial distribution and drivers of the smallholder oil palm-related conversion of peat swamp forests. In contrast to existing studies based on farm surveys, we used state-of-art maps of smallholder oil palm plantings, derived from 2019 remote sensing data. Spatial data about socioeconomic and biophysical factors (e.g. mills, roads, water ways, and concessions) was then used to develop logistic regression models to investigate the relative influence of these factors. We show that the spatial patterns of smallholder oil palm plantings are distinct from those of industrial oil palm plantations, revealing the critical roles of roads, especially service roads, residential roads and tracks, in driving smallholder oil palm expansion within peatlands. We found that 90% of smallholder oil palm areas were located within 2 km of roads and 25 km of mills. The mean likelihood of a given land area being converted from peat swamp forests to smallholder oil palm declined rapidly with increasing distance from roads and mills. In addition to roads and mills, land use zones (e.g. the setting of concessions and migration settlements) and other environmental factors (e.g. precipitation and elevation) were identified as important drivers of smallholder oil palm expansion on peatland. Based on these findings, we identify priority regions for the protection of the remaining peat swamp forests in Indonesia and discuss strategies for tackling these sustainability challenges on local and global scales.

1. Introduction

Tropical peatlands represent 10%–30% of all terrestrial carbon storage (Hodgkins *et al* 2018, Cooper *et al* 2020) and support some of the most biodiverse plant and animal communities on Earth (Posa *et al* 2011, Harrison and Rieley 2018). Approximately 56% of tropical peatlands are found in Southeast

Asia (Page *et al* 2011), where they were formed by the accumulation and inundation of plant debris over thousands of years (Takada *et al* 2016). Tropical peat swamp forests provide a range of ecosystem services and support livelihoods based on 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, such as oil palm (*Elaeis guineensis*) plantations (Koh *et al* 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 peat swamp forests to monoculture oil palm plantations has led to the loss of endemic biodiversity in these ecosystems (Giam *et al* 2012). The conversion of peatlands is accompanied by land clearance fires that often escape control (Adrianto *et al* 2020). When fires burn into the peat they release large amounts of soil carbon into the atmosphere, contributing about 840 Mg C ha⁻¹ to the growth of atmospheric CO₂ (Cooper *et al* 2019, Vásquez *et al* 2021). Since peatland could be reclaimed for farming and logging, sustainable management is required to achieve the balance of appropriate agricultural and forest production, better rural livelihood, favorable ecological services and biodiversity, and minimal greenhouse gas emissions (Surahman *et al* 2018). In addition, reducing peatland deforestation and fires and restoring degraded peatland are important management goals for diverse stakeholders (Hergoualc'h *et al* 2018).

Global demand for palm oil has been a major driver of land use change, especially in Indonesia (Wicke *et al* 2011, Shigetomi *et al* 2020). Between 1990 and 2018, the area of oil palm cultivated in Indonesia increased from 1 million ha to 14 million ha (Directorate General of Estate Crops, Ministry of Agriculture, 2019). During this period, the area of oil palm cultivated by smallholders increased from 0.3 million ha to 6 million ha, while industrial plantations jumped from 0.5 million ha to 8 million ha. Although the expansion and impacts of industrial oil palm plantations has been an area of active research over the past decade, attention to the smallholder sector has been lacking, especially for independent owners of oil palm areas smaller than 25 ha (Lee *et al* 2014, Austin *et al* 2017). Besides global demand and higher profitability, the spatial scale of oil palm expansion could also be driven by a list of local socioeconomic factors and policies, such as the establishment of oil palm concessions and mills (Austin *et al* 2015, Euler *et al* 2016, Ordway *et al* 2019) the transmigration program (Feintrenie *et al* 2010, Gatto *et al* 2015), and land rents (Lim *et al* 2019). In addition, road construction has been recommended for rural development and oil palm development (Obiechina Chirs 1986, van de Walle 2002, Khandker *et al* 2009, Mu and van de Walle 2011), but has also caused unintended consequences for deforestation (Gaveau *et al* 2009, Vijay *et al* 2018). Meanwhile, the reduction of available farmland has pushed both industrial plantations and smallholders to enter peatland areas (Areal Penggunaan Lain (APL)) and even peatlands in forested zones (Shivakumar and Bell 2015, Jelsma *et al* 2017, Schoneveld *et al* 2019). Due to a decentralization policy since 2001, limited efforts are made

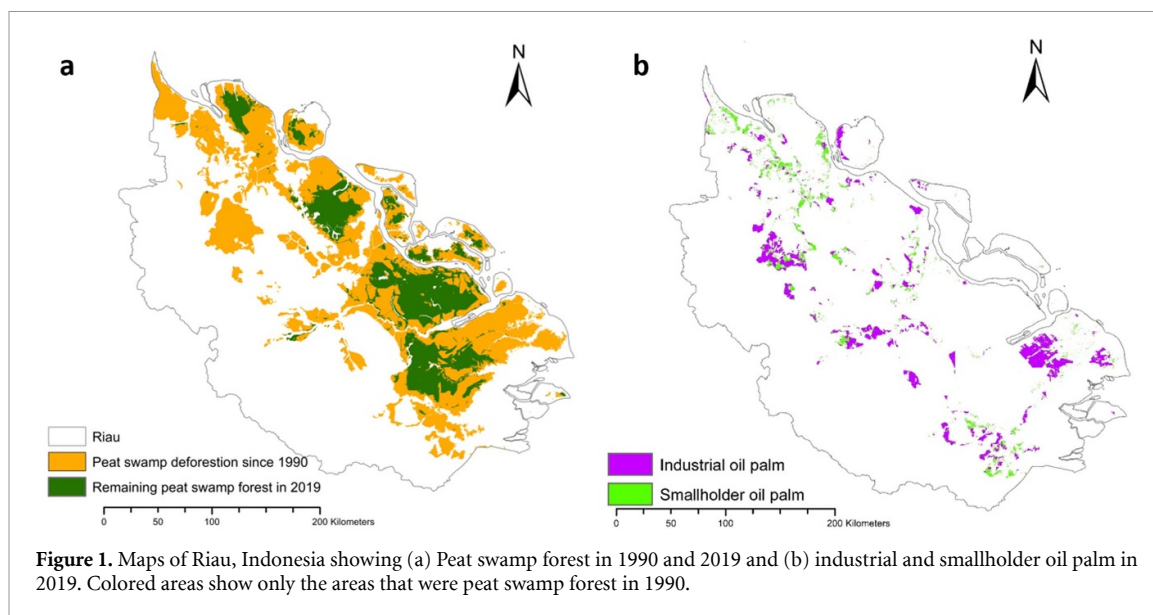
to prevent smallholder oil palm from entering the undeveloped area surrounding oil palm mills (Naylor *et al* 2019). Moreover, farmers' insufficient awareness of peatland regulations and poor field monitoring and law enforcement could also lead to the conversion from peatland to oil palm (Uda *et al* 2020) 2.

The drivers and impacts of industrial oil palm plantations have been well documented, but we still lack the same information for smallholder oil palm, especially during their expansion onto peatlands. Therefore, we aim to understand the spatial distribution and drivers of smallholder oil palm expansion into peat swamp forests and identify strategies for slowing the deforestation of the remaining peat swamp forests. We focused our study on the province of Riau, which has the second largest peatland area, but is the largest producer of oil palm among Indonesian provinces and which has rapid smallholder oil palm expansion. We used the 2019 map of oil palm areas with closed canopies (Descals *et al* 2021), which excluded immature plantations. We characterized the land transitions from peat swamp forests in 1990 in Riau into four types of land cover in 2019 (smallholder oil palm, industrial oil palm, remaining peat swamp forests, and other land covers). We developed a spatial logit model, for Riau, to identify the major drivers of current smallholder oil palm in land that was peat swamp forest in 1990. We hypothesized that an increasing distance to mills, roads, and waterways could have a negative effect on the expansion of smallholder oil palm, while potential yield, population density and migrant villages were expected to have a positive effect. We also hypothesized that biophysical factors, like precipitation, elevation and slope are strongly associated with conversion from peat swamp forests to smallholder oil palm. Our findings could prove insightful for the balancing of sustainable oil palm expansion in Indonesia with the effective protection of remaining peat swamp forests. To the best of our knowledge, this study is among the first to characterize the spatial pattern of smallholder oil palm plantings from socioeconomic perspectives and to use spatial-econometric modeling to analyze the drivers of smallholder oil palm expansion into peat swamp forests in Indonesia.

2. Method

2.1. Site description

Riau province is the largest producer of palm oil in Indonesia, and oil palm expansion is one of the major drivers of deforestation on peatlands in Riau (Taheripour *et al* 2019, Adrianto *et al* 2020). Smallholder oil palm area in Indonesia increased from 300 000 ha in 1990 to 5.8 Mha in 2018 (Directorate General of Estate Crops, Ministry of Agriculture, 2019). Riau accounted for 41% of this area in 2018, including 1.46 Mha of smallholder oil palm plantations and 0.76 Mha of industrial oil palm plantations.



Industrial and smallholder oil palm expansion both encroached into peat swamp forest in Riau (as shown in figure 1(b)). Since 1990, 56% of the peat swamp forest has been granted to private companies as concessions for establishing plantations, with 22.5% for oil palm and 35.6% for wood fiber concessions, however there is a small overlap between oil palm and wood fiber concessions (WRI 2019, authors' calculation based on figure S7 available online at stacks.iop.org/ERL/17/044015/mmedia).

According to the Indonesian Village Potential statistics (BPS, 2018), around 30% of villages are Javanese and Batak as the majority tribe/ethnicity of their communities. These villages are considered as migrant villages in our analysis, because the Javanese and Batak are ethnic groups that migrated to Riau mainly for oil palm plantations (Jelsma *et al* 2017, Yusuke and Junji 2018). Javanese living in Riau could be Javanese migrants who migrated from other provinces in Sumatra, or transmigrants who migrated directly from the island of Java. The Batak group migrated to Riau mainly from North Sumatra due to the difficulty of land availability (Potter 2016). Transmigration was a policy from the Dutch colonial era that continued after Indonesia's independence, to resettle people from densely populated islands such as Java. Villages that were labelled non-migrant villages in our study were considered local villages and had a dominant tribe/ethnicity belonging to the Melayu Riau, Melayu, Banjar, Minangkabau and Bugis groups (table S1).

In Riau, both temperature and precipitation are relatively high over peatland areas. Between 1970 and 2000, average annual temperatures ranged from 26.07 °C to 26.87 °C and, although the average annual precipitation was 2447 mm, annual precipitation ranged from 2166 mm to 3265 mm (Fick and Hijmans 2017). The peatland areas are relatively flat, with an

average slope 2.04° (0°–25.47°) and an average elevation of 24.5 m (–13 m to 116 m) above mean sea level (NASA SRTM 2013).

For Riau province, we investigated the characteristics of land uses in 2019, in areas that were classified as peat swamp forests (some of which were degraded) in 1990. Between 1990 and 2019, peat swamp forests decreased by 2.16 Mha (orange area in figure 1(a); Miettinen and Liew 2010) to around 1 Mha (dark green in figure 1(a)). Current land-use for oil palm does not necessarily indicate that it was the direct or immediate driver of peat swamp deforestation, since intermediate land-uses could have occurred during the intervening 29 year period, before conversion to oil palm. We do not account for these potential transitory land uses prior to 2019. Although deforestation of peat swamp forests has been severe since 1990 (figure 1(a)), 1/3 of peat swamp forests areas remain, suggesting there are still opportunities for incorporating new understanding of the drivers of peat swamp deforestation into conservation planning.

2.2. Data description

The data used in this study include maps of oil palm cultivation in 2019 and maps showing oil palm mills, roads, waterways, travel time to cities, oil palm and wood fiber concessions, biophysical factors (elevation, temperature, slope, and precipitation), population density, potential yield, and migration data (table 1). All maps were reprojected to the Asia South Albers Equal Area Conic coordinate system and resampled to 30 m × 30 m cells using the nearest neighbor (discrete variable) or bilinear (continuous variable) method and using ArcMap 10.4.

Oil palm maps were acquired from the work described by Descals *et al* (2021), and consisted of smallholder and industrial closed canopy oil palm

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 <i>et al</i> (2021)	10 m × 10 m	2019
Industrial oil palm (OP_IND)	Presence or absence of industrial oil palm	Descals <i>et al</i> (2021)	10 m × 10 m	2019
Predictor variables				
Economic factors (E)				
Distance to oil palm mills (km)	Grid cell distance to nearest oil palm mills	Okarda and Manalu (2018)	Point	2017
Distance to roads (km)	Grid cell distance to nearest roads	Humanitarian OSM team (2020)	Polyline	2020
Distance to waterways (km)	Grid cell distance to nearest waterways	Humanitarian OSM team (2020)	Polyline	2020
Travel time to cities (h)	Grid cell travel time to nearest cities with population > 50k	Weiss <i>et al</i> (2018)	30 arc second	2015
Biophysical factors (B)				
Precipitation I (cm)	Annual precipitation	Worldclim.org	1 km × 1 km	1970–2000
Precipitation II (cm)	Precipitation of driest quarter	Worldclim.org	1 km × 1 km	1970–2000
Temperature (°C)	Annual mean temperature	Worldclim.org	1 km × 1 km	1970–2000
Slope (degree)	Gridded slope based on elevation	SRTM (NASA Shuttle Radar Topography Mission (SRTM) 2013)	1 arc second	2013
Elevation (m)	Gridded elevation	SRTM (NASA Shuttle Radar Topography Mission (SRTM) 2013)	1 arc second	2013
Potential yield (t ha ⁻¹)	Potential yield with high inputs	IIASA/FAO (2012)	10 km × 10 km	1961–1990
Land classification (L)				
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
Land legal status (Kawasan Hutan)	Status of land, including non-forest land, production forest, and other forest	Ministry of Environment and Forestry (2017)	Polygon	2017
Social factors (S)				
Population density (persons km ⁻²)	Population count per km ²	LandScan (2019)	30 arc second	2019
Migrant village dummy	Grid cell value = 1 if the majority of ethnicity is Javanese in the village, otherwise 0	Indonesian Village Potential survey or Potensi Desa (PODES)	Polygon	2018

data derived from a convolutional neural network classification model, applied to Sentinel 1 and 2 remote sensing data at a 10 m × 10 m spatial resolution. The model maps oil palm locations using the differences between smallholder and industrial oil palm plantations in field shape, field size, tree ages, and the density of trail, road, and canal networks surrounding the plantations. Compared to industrial oil palm plantations, smallholder plantations tend to

be less regular in shape, more heterogeneous in tree ages, and the homogenous cluster formed by smallholder plantations have less dense trail and road networks (Descals *et al* 2021). The map does not distinguish between sub-types of smallholdings, such as independent smallholders, who individually manage their oil palm, and scheme smallholders who are associated with an oil palm company. The user accuracy of the map for industrial and smallholders

was $88.22\% \pm 2.73\%$ and $76.56\% \pm 4.53\%$, and the producer's accuracy was $75.78\% \pm 3.55\%$ and $86.92\% \pm 5.12\%$, respectively. The 1990 map of peat swamp forest was derived by extracting peat swamp forests (including pristine and degraded designations) in Riau from land cover maps provided by the Centre for Remote Imaging Sensing and Processing and Miettinen and Liew (2010). The 2019 peat swamp forest map (including pristine and degraded) was derived from the land cover map of the Indonesian Ministry of Environment and Forestry. We overlaid the 1990 peat swamp forest map on to the 2019 map of smallholder and industrial oil palm and the 2019 map of remaining peat swamp forest, and assigned the 'other land uses' class to any additional non-forest areas within the 1990 peat swamp forest area. This allowed us to derive four 2019 land cover types within previous peat swamp forest areas: smallholder oil palm, industrial oil palm, remaining peat swamp forest, and an 'other land uses' class that included shrubs, other smallholder crops and other types of plantation, etc.

The list and spatial locations of oil palm mills in 2017 are from Okarda and Manalu (2018) (www.cifor.org/knowledge/dataset/0098/). They compiled the list of oil palm mills from supply chain documents in traceability reports for major palm oil processors in Indonesia. Spatial locations were verified 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 had more data about Riau's oil palm mills. Based on the spatial location of oil palm mills, we calculated the Euclidean distances from each $30\text{ m} \times 30\text{ m}$ pixel to the nearest oil palm mill.

The polyline maps of roads and waterways are from the Humanitarian Data Exchange (HDX), produced by the Humanitarian OpenStreetMap (OSM) team, which was updated in 2020. The map distinguishes roads by function and importance, and includes any kind of road, street, or path within the road network, such as highways (primary, secondary, tertiary), residential roads (connecting houses), service roads (within industrial estates, parks), and tracks (mostly for agricultural or forestry use). Waterways were distinguished by flow types (free flow, pipe flow) and how it was produced (man-made, natural), such as canal, drain, ditch, river, or stream. Based on the roads and waterways map, we calculated the Euclidean distances of each pixel ($30\text{ m} \times 30\text{ m}$) to the nearest road and waterway. Travel time to major cities was from a map developed by the European Commission and the World Bank in 2015 (Weiss *et al* 2018). The publicly available, 30 arc-second, travel times to cities with populations larger than 50 000 people (using land- or water-based means of travel and a cost-distance algorithm) were resampled to $30\text{ m} \times 30\text{ m}$ cells using a bilinear method.

Oil palm and wood fiber concessions data are from the World Resource Institute, and are available from Global Forest Watch, based on data provided by the Indonesia Ministry of Environment and Forestry. Concessions data display the boundaries of areas allocated by governments to private companies. Oil palm concessions refers to land for industrial-scale oil palm plantations. Oil palm concessions are public lands allocated to private companies that are also required to include local communities as plasma farms through oil palm production, including training, supplies of seedlings and fertilizer, and buying oil palm fruits. Wood fiber concessions are used to establish fast-growing tree plantations for wood pulp and paper production.

The 2017 Kawasan Hutan map from the Ministry of Environment and Forestry shows different forest use zones in Indonesia, which include permanent production forest (HP), limited production forest (HPT), convertible production forest (HPK), protected forest (HL), nature parks (TWA), wildlife reserve (SM), nature reserve/conservation area (KSA/KPA) and non-forest area (APL). In this study, we grouped all forest use zones into three groups: non-forest area (APL), production forest (HP, HPT, HPK), and other forest.

Historical precipitation and temperature data for 1970–2000 are from the WorldClim.org (Fick and Hijmans 2017). We collected annual precipitation, precipitation of the driest quarter, and annual mean temperature at a 30 s ($\sim 1\text{ km}^2$) resolution for our study area. Terrain data, including elevation and slope were compiled from the Shuttle Radar Topography Mission (NASA Shuttle Radar Topography Mission (SRTM) 2013), which is at one arc-second (approximately 30 m) resolution.

Population density data was collected from LandScan Global 2019 (Dobson *et al* 2000), which provides an ambient population distribution (average over 24 h) at the approximately 1 km ($30'' \times 30''$) spatial resolution. This database is updated annually and has been widely used in the previous studies (Linard *et al* 2011, Tateishi *et al* 2011).

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 potential productivity of land under different management regimes (IIASA/FAO 2012). Considering that, like industrial plantations (Woittiez *et al* 2018, Darras *et al* 2019), smallholder oil palm production is also market oriented and requires high fertilizer input levels, we used the potential yield of palm oil with high input levels under rain-fed conditions over the historical period from 1961 to 1990. This potential yield map is similar to the suitability map generated by Pirker and Mosnier (2015).

Since migrants may have different preferences for oil palm and could adopt this crop earlier and faster than indigenous people (Gatto *et al* 2015), we used a migrant village dummy variable to estimate the impacts of migrant villages on smallholder oil palm expansion into the peat swamp forest. Based on a 2018 village potential survey, village communities with a Javanese majority tribe/ethnicity are treated as migrant villages, otherwise as non-migrant villages (PODES).

2.3. Model of smallholder oil palm expansion

Multivariate logistic regression modeling is widely used in the analysis of deforestation patterns, including those due to oil palm expansion, potentially showing the relative influences of different determinants on the probability of expansion (Gaveau *et al* 2009, Castiblanco *et al* 2013, Austin *et al* 2015, Shevade and Loboda 2019). We used this model approach to estimate the probability that the current (2019) land cover is closed-canopy smallholder oil palm in areas that were peat swamp forest in 1990. The response variable in logistic regression is a binary 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 and socioeconomic factors. The response function is the logit transform of the probability $p \in [0, 1]$ that the response variable takes the value 1:

$$\text{logit}(p) = \log\left(\frac{p}{1-p}\right).$$

Since the logit is within the interval $[-\infty, +\infty]$, it could be modelled as a linear combination of predictor variables

$$\text{logit}(p) = \gamma'X + \delta'P \times C1 + \beta,$$

where X is a vector of variables listed in table 1, γ is a vector of coefficients for each variable and β is a scalar parameter. $P \times C1$ represents the interaction terms between proximity variables (distance to mills, distance to roads, distance to waterways) and the oil palm concessions dummy, while δ is a vector of coefficient for interaction terms. All parameters are estimated using a maximum likelihood approach based on the GLM function in the R statistical programming language (R Core Team 2017).

Grid-based data often exhibits spatial dependence and autocorrelation, which increases systematically with the resolution level (Chou 1991). But this violates the assumption of independent observations that logistic regression requires. Therefore spatial sampling is essential, since dependent data could easily result in the rejection of null hypotheses and lead to incorrect conclusions about the significance of parameters. Meanwhile, the sample size should be large enough to represent the variability of geospatial factors within the study area, but cannot be so large

as to violate the assumption of independent observations due to spatial autocorrelation (Heckmann *et al* 2014). To determine a suitable sample size, we replicated GLM regressions 100 times at each sample size from 1000 to 10 000 by adding 100 each time and selected variables by stepwise selection using the Akaike information criterion (AIC), and calculated the frequency of each variable selected at different sample sizes (figure S1). From this exercise, we selected 9000 pixels (30 m \times 30 m) as our sample size since the frequency of model variables were stable when the sample size was greater than 9000.

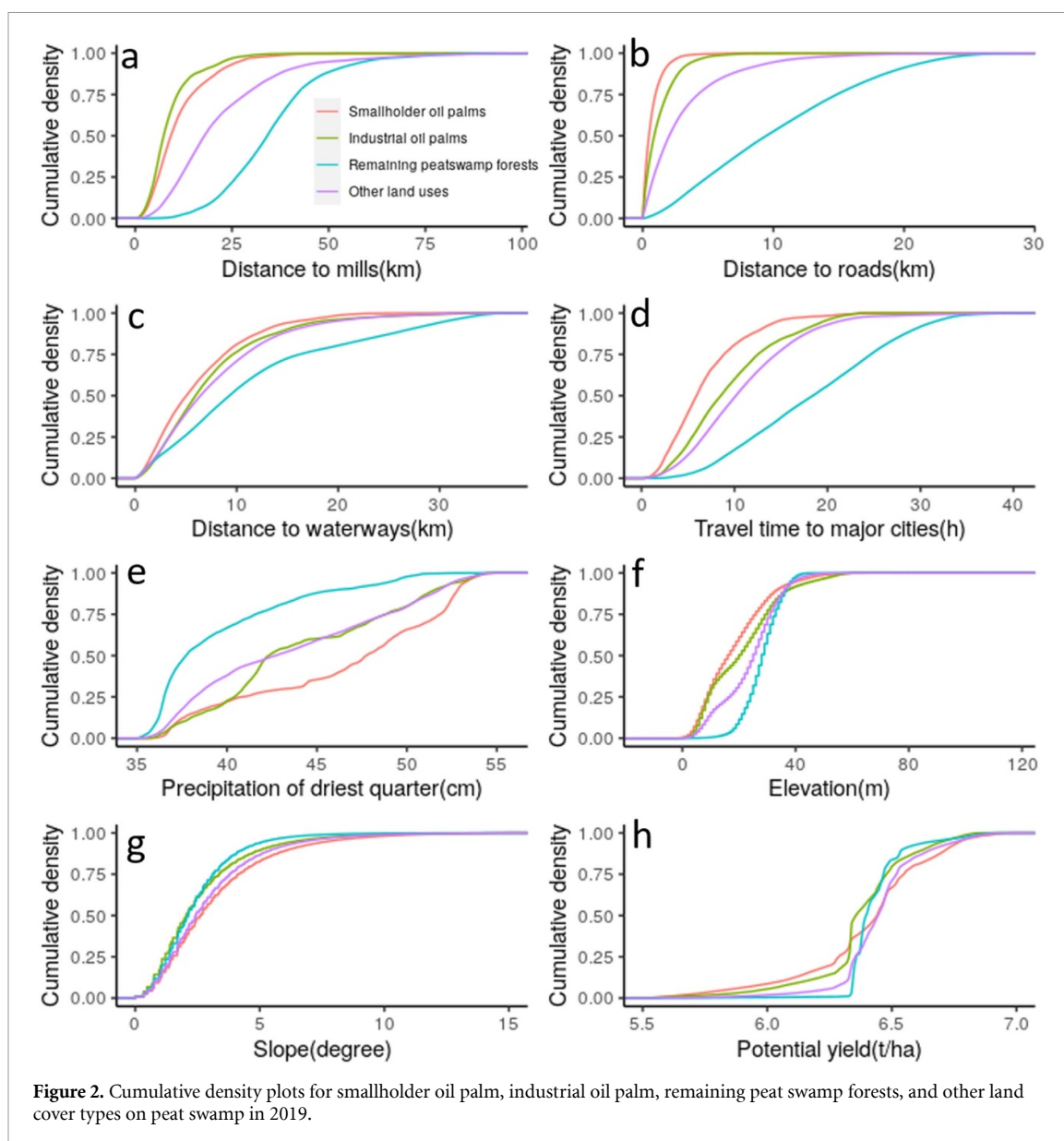
Besides sample independence, the absence of multi-collinearity is an important prerequisite for logistic regression. To avoid the impacts of multi-collinearity, we tested the pairwise correlation of all model effects using Pearson's method. The distance to roads and travel time to major cities was also found to be highly correlated, and the former was selected, given the importance of roads in rural development. Annual precipitation and precipitation of the driest quarter were highly correlated, so only precipitation of the driest quarter was used.

Logistic regression was performed using the glm and stepAIC functions of the MASS package in R (Venables and Ripley 2002). Based on the sample dataset, we began with a full model using all of the variables, except those that were highly correlated, and chose the final model via stepwise AIC. To address the issue of spatial autocorrelation, we included a spatial autocovariate term in the model, which was calculated using spdep and lattice packages in R, based on the method described in Bardos *et al* (2015). We checked the spatial autocorrelation with Moran's I test of the residuals. Model validation and accuracy was assessed using the receiver operating characteristic (ROC) curve and area under the ROC curve, which can be used to select optimal threshold values and reasonable estimates of prediction accuracy of rare events (supplementary figure S6). Robust standard errors were calculated using White's estimator via the foreign and sandwich packages in R.

3. Results

3.1. Spatial characteristics of smallholder oil palm distribution

First we report on the spatial characteristics of smallholder oil palm in comparison to industrial oil palm, peat swamp forest and other land use, considering the distance to roads and mills, travel time to big cities, and ecological factors. In Riau, peat swamp forests covered more than 3.1 million ha of peatland in 1990; but by 2019, 15% (465 000 ha) of these forests had become mature oil palm. A third of this mature oil palm extent (155 000 ha, 5% of peat swamp forests area in 1990) was identified as smallholder plantations and 310 000 ha as industrial

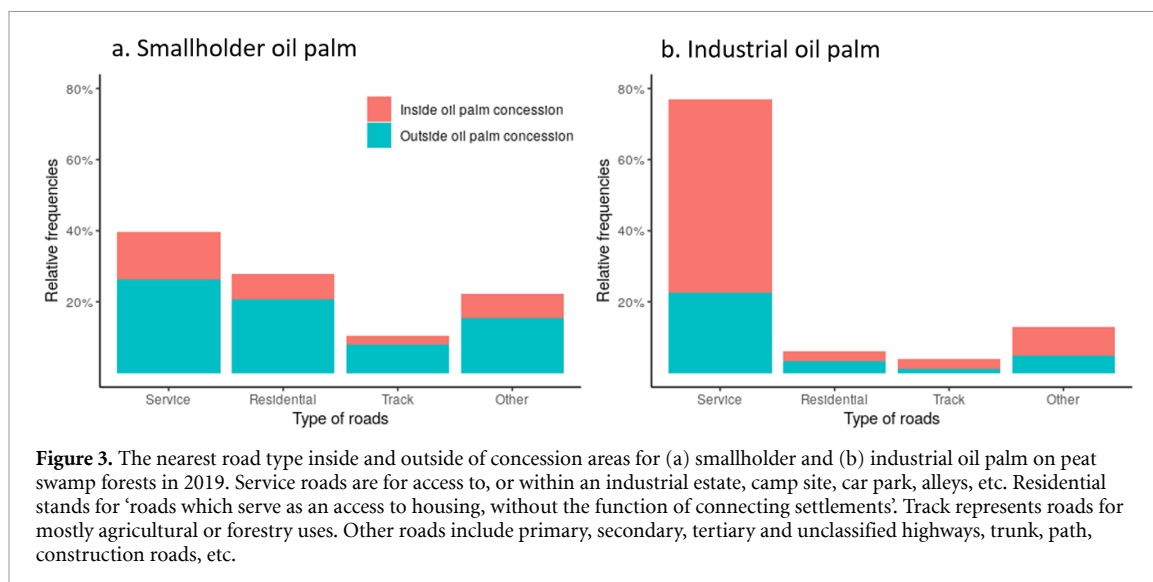


plantations. Moreover, 57% (85 000 ha) of smallholder oil palm is within the forest zones (especially production forests, table S6), which do not comply with the Indonesian forestry law (Hergoualc'h *et al* 2018). Although the majority of smallholder oil palms were planted outside concessions, around 50 000 ha (30%) were located inside oil palm concessions, while about 21 700 ha (14%) of smallholder oil palm was present inside wood fiber concessions. By contrast, the majority (68%) of industrial oil palm plantations were located inside oil palm concessions, and only 5% were found in wood and fiber concessions.

In terms of the distance to roads, smallholder oil palm areas were found to be distinct from other land covers or uses in three ways. First, the mean distance from smallholder oil palms to the nearest road (722 ± 806 m) is much shorter than those for industrial oil palm (1292 ± 1330 m). In addition, 75% of smallholder oil palm is located within 1 km of the nearest road, versus 2 km for industrial oil palm

(figure 2(b)). Second, for all land within 0.5 km of a road, smallholder oil palm was the majority of land cover, with frequency decreasing as distance to the nearest road increases (figure 3). Third, service roads (i.e. roads within or providing access to estate plantations) accounted for 77% of all of the nearest roads for industrial oil palms while making up only 40% for smallholder oil palm, with the remainder being 27% residential roads (i.e. roads connecting houses), 10% tracks (i.e. used for agriculture and forestry), and 23% other types (figure 3).

The distance to mills for smallholder oil palm was found to be significantly greater than for industrial oil palm, especially inside oil palm concessions, but was smaller than for other land cover types. The average distance to the nearest mill was 9.1 ± 6.4 km for industrial oil palms and 11.4 ± 8.1 km for smallholder oil palm. Within oil palm concessions, the average distance to mills was 8.4 ± 6.4 km for industrial oil palm but 11.8 ± 7.8 km for smallholder oil palm.



Travel time to major cities for smallholder oil palm is considerably shorter than for industrial oil palm, remaining peat swamp forest, and other land uses. The average travel time from smallholder oil palm to the nearest city with more than 50 000 people is 6.8 ± 4.2 h, compared to 9.4 ± 5.2 h for industrial oil palm, and 18 ± 7.9 h for remaining peat swamp forests. Moreover, 75% of smallholder oil palms are within 9 h of a major city.

Considering oil palm distribution in relation to ecological factors, we found that smallholder oil palm is more likely to be located in regions with higher precipitation, higher slope and lower elevation compared with other land cover types (figures 2(e)–(g)). The precipitation of the driest quarter is 464 ± 57 mm for smallholder oil palm and 441 ± 52 mm for industrial oil palm. The annual precipitation is 2647 ± 253 mm for smallholder oil palm and 2555 ± 311 mm for industrial oil palm. The average slope of smallholder oil palm is $3.2^\circ \pm 2.4^\circ$, and it is $2.6^\circ \pm 2.0^\circ$ for industrial oil palm. The average elevation of smallholder oil palm is 18.3 ± 11.6 m, and it is 21.0 ± 13.0 m for industrial oil palm. Higher precipitation and steeper slope are less favorable conditions for oil palm cultivation in the region.

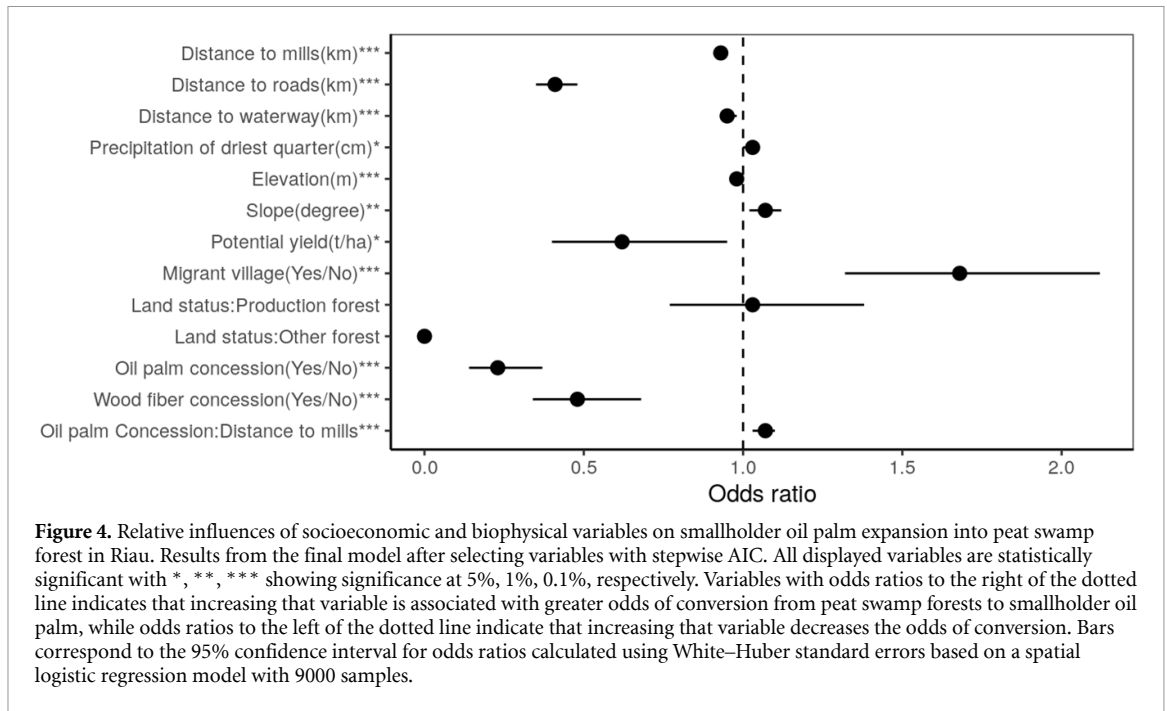
3.2. Drivers of smallholder oil palm expansion

Our second result is the major socioeconomic and ecological drivers of smallholder oil palm expansion based on spatial logistics regression. Our logistic regression results show that the distance to the nearest roads, mills, and waterways each have significantly negative effects on smallholder oil palm expansion into peat swamp forests (figure 4). In addition, smallholder oil palm is more likely to expand within migrant villages but less likely within oil palm and wood fiber concessions. Biophysical factors, like precipitation, elevation and slope, are statistically significant. Our results show that potential yield has a

negative effect on the expansion of smallholder oil palm, which was hypothesized to be positive. Forest zones designated by the government had limited impact on restricting the expansion of smallholder oil palms into peat swamp forest areas. Population density and temperature were tested in our model development, but their effects were mostly not significant (table S2).

The distance to the nearest road was found to have a negative effect on the conversion from peat swamp forests to smallholder oil palm. The odds of a given peat swamp forest area being converted to smallholder oil palm decreased by 59% (odd ratios = 0.41, 95% CI [0.35, 0.48]) for every kilometer increase in distance to the nearest road. We also replicated our regression 100 times with non-replacement samples, which all demonstrated the robustness of our observation for road effects (supplementary figure 5). Conversely, the distance to waterways was weakly associated with the conversion from peat swamp forest to smallholder oil palm. The odds of a given peat forest area being converted to smallholder oil palm dropped by 5% (odd ratios = 0.95, 95% CI [0.93, 0.98]) for every kilometer increase in distance to the nearest waterways.

The distance to the nearest mill significantly limits the expansion of smallholder oil palm. The odds of a given peat forest area being converted to smallholder oil palm outside oil palm concessions decreases by 7% (odd ratios = 0.93, 95% CI [0.91, 0.95]) for every kilometer increase in distance to the nearest mill. Inside oil palm concessions, the distance to mills has no significant effect on conversion (table S3). Therefore, the distance to mills has different effects on the conversion from peat swamp forests to smallholder oil palm inside and outside oil palm concessions. Smallholder oil palm within oil palm concessions might be scheme-smallholders, who have their own network of transportation to



bring fresh fruit bunches to mills and have guaranteed access to mills, since they are contractually bound to companies.

As expected, peat swamp forests inside oil palm and wood fiber concessions are less likely to be converted to smallholder oil palms than outside these concessions. According to our model, the odds of a given peat forest area being converted into smallholder oil palm within oil palm concessions are about 77% lower (odd ratios = 0.23, 95% CI [0.14, 0.37]) than the odds for outside oil palm concessions. The odds of an area being smallholder oil palm within wood fiber concessions are about 52% lower (odd ratios = 0.48, 95% CI [0.34, 0.68]) than the odds for outside wood fiber concessions. Typically, smallholder oil palm plantations would not be present in oil palm concession areas, and even less so in wood fiber concession areas, since the company would maximize the concession area for their own industrial plantations. Nevertheless, our analysis revealed a total of 71 700 ha of smallholder oil palm in oil palm and wood fiber concessions.

Peat swamp forests within those migrant villages have a higher likelihood of being converted into smallholder oil palm compared to non-migrant villages. The odds of a given peat forest area being converted to smallholder oil palm within migrant villages is about 68% higher (odd ratios = 1.68, 95% CI [1.32, 2.12]) than the odds for non-migrant villages. However, these results do not mean that smallholder oil palm is planted and owned by migrants, since these plantations could be under an absentee-landowner scheme where the owners reside in cities while employing people to manage their land (Jelsma *et al* 2017). Our modelling results only demonstrate that the likelihood of peat swamp forest

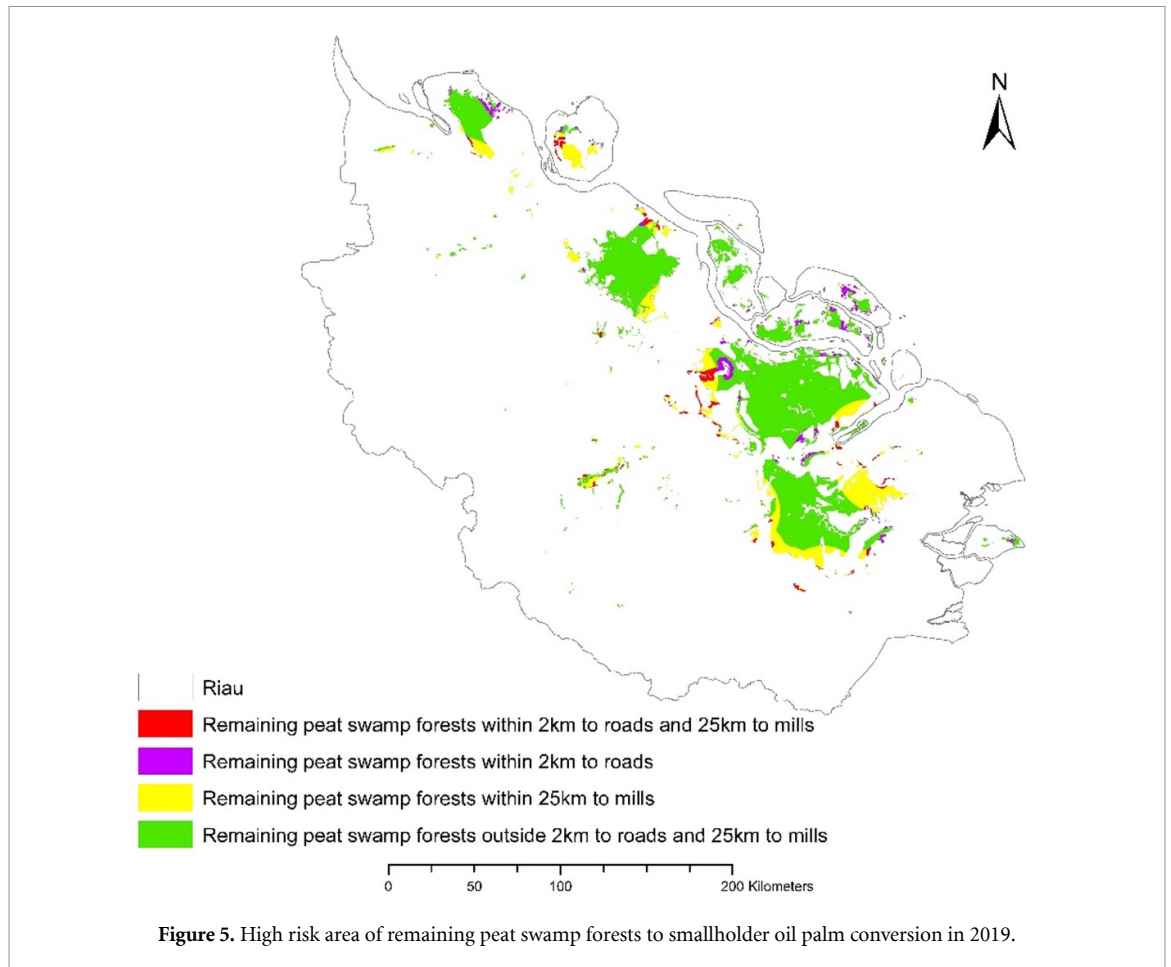
being converted into smallholder oil palm in migrant villages is higher than in non-migrant villages.

Biophysical variables, including precipitation, elevation and slope, also have significant influence on the expansion of smallholder oil palm over peat. The likelihood of swamp peat forest conversion to smallholder oil palm increased in the regions with increasing precipitation, decreasing elevation and increasing slope. The odds of a given peat forest area being converted into smallholder oil palm rises by 3% (odd ratios = 1.03, 95% CI [1.00, 1.05]) with each 1 cm increase in precipitation of the driest quarter, climbs 2% (odd ratios = 0.98, 95% CI [0.97, 0.99]) with each 1 m decrease in elevation, and rises by 7% (odd ratios = 1.07, 95% CI [1.02, 1.12]) with each 1° increase in slope.

Potential yield shows a statistically significant and negative effect on smallholder oil palm expansion over peatland in our model. This is different to our hypotheses that peat swamp forests with higher potential yield tend to be converted into smallholder oil palm. Our results indicate that small farmers prioritize the accessibility of land, considering the significant effects of distance to roads and mills, rather than the potential yield of the land. In addition, the ability to access lands with high yields may not be within the reach of small farmers and be acquired by companies before the expansion of smallholder oil palm plantations.

3.3. Remaining peat swamp forests and regions with high deforestation risk

Our third result shows the regions at the highest risk of conversion to smallholder oil palm for the remaining peat swamp forests in Riau. Since 1990, 70% Riau's peat swamp forests have been cleared and



the majority of the remaining forests in 2019 have been degraded. For those remaining 940 000 ha peat swamp forests, we identified regions that are under high risk of further conversion to smallholder oil palm plantations. High risk areas were within 2 km of roads and 25 km of mills (figure 5). These criteria were chosen because 90% of current smallholder oil palm converted from peat swamp forest was located within 2 km of a road or 25 km of a mill (table S4). We calculate that 29 470 ha of remaining peat swamp forest is located in areas that meet both of these criteria, 66 598 ha is located within 2 km of a road, and 195 687 ha is located within 25 km of a mill.

4. Discussion

4.1. The controversial role of roads for sustainability

Roads are critical for promoting rural and local development and reducing poverty through improved agricultural production and output prices, and lowered input and transportation costs. Our results confirm that smallholder oil palm has increased dramatically in areas close to mills and roads (Cramb and Sujang 2013). Distance to roads is especially important for smallholder oil palm farmers because of major production and harvest practices, such as

transporting inputs (like fertilizer) and outputs (like fresh fruit bunches), and using large agricultural machinery. Therefore, improving access to roads, as well as mills, could benefit smallholders by reducing marketing costs and facilitating production, harvest, and the processing of fresh fruit bunches, consequently improving socioeconomic conditions for smallholders. However, road development in peatland with high biodiversity and carbon storage may have detrimental effects for the environmental sustainability of a region and the world (Chomitz and Gray 1996, Laurance *et al* 2009, Barber *et al* 2014, Gaveau *et al* 2021).

While our results demonstrate the controversial role of roads in improving socioeconomic conditions, potentially at the expense of environmental sustainability on local and global scales, they also present potential opportunities for addressing sustainability challenges through improving the design of road networks. One opportunity is the identification of peat swamp forest areas facing a high risk of conversion to smallholder oil palm plantations and the prioritization of these regions for protection; for example, Gaung Anak Serka district in Indragiri Hilir, Dayun district in Siak, Rangsang in Kepulauan Meranti, Rupert in Bengkalis, and Sinaboi district in Rokan Hilir (figure 5). Peat swamp forests

in these regions could be added as new protected areas, or placed under the peat moratorium by the government. Meanwhile, the government could provide more extension and communication services in these high-risk areas and help smallholders identify effective ways to increase income other than by converting peat swamp forests into oil palm, such as improving the yield and production on current lands (Saleh *et al* 2018).

Another opportunity is to improve the design of new road networks by considering their impacts on remaining peat swamp forests and on smallholder livelihoods. For example, when new roads are planned and developed to promote local development, the use of areas that are close to remaining peat swamp forests (e.g. within 2 km) could be minimized, or even avoided. In addition, given the finding that smallholder oil palm is usually distributed along service roads, residential roads, and tracks for agriculture and forestry, policies that restrict development of these types of roads in regions with high carbon storage and biodiversity could effectively reduce the likelihood of smallholder oil palm establishment, and potentially redirect smallholder farmers' efforts towards enhancing productivity on existing agricultural land.

4.2. Implication for concessions and migration policies

Our findings indicate that the distance to oil palm mills, that are primarily established within or near oil palm concessions and operated by private oil palm companies, has significant impacts upon smallholder oil palm expansion outside of oil palm concessions, but not inside oil palm concessions. Previous studies also found that smallholder oil palm cultivation in Sumatra depends greatly on access to nearby oil palm mills that are generally within government-granted concessions to palm oil companies (Euler *et al* 2017). Therefore, government policies, such as granting concessions, should consider the future land use dynamics they are likely to initiate. By accounting for the settlement patterns of smallholder farmers, both inside and outside concessions, unintended negative consequences for the conservation of the remaining peat swamp forests can be avoided. Our results include examples of smallholder farms located within concession areas, and industrial plantations that extend outside of concessions. Overlapping concession boundaries associated with the pulpwood and palm oil sectors have also been noted by other studies (Abood *et al* 2015, Gaveau *et al* 2017). Therefore, updating concession boundaries, marked on-the-ground to resolve overlaps, is one goal of the One Map initiative launched by Indonesia. Resolving these issues can be useful in identifying where remaining peat swamp forest is located, quantifying the risk of forest conversion, and defining the

resources required to ensure their protection. Based on our analysis, more than 30% of remaining peat swamp forest is within concessions, emphasizing the need for clear and updated concession boundaries. Moreover, remaining peat swamp forests inside concessions could be used to generate carbon credits, if international carbon markets become well enough developed (Dunn and Freeman 2011).

Our results support previous findings describing the effects of migration policies, specifically that the planting of oil palm is adopted earlier and more intensively in migrant villages than in non-migrant villages (Gatto *et al* 2015). This may be because transmigrants from Java were often the first small farmers to adopt oil palm as part of government schemes for estate-plasma projects (Euler *et al* 2017, Santika *et al* 2019). In Riau, the population that migrated from other provinces increased from 0.7 million in 1990 to 1.9 million in 2010, accounting for 35% of the total population (Badan Pusat Statistik, Indonesia). This accelerated oil palm development, and caused land disputes and deforestation (Widyatmoko and Dewi 2019). Therefore, the siting of future transmigration settlements should avoid areas of high conservation value such as peat swamp forests.

4.3. Uncertainties and limitations

Although there are various uncertainties in the maps and data used in this study, we believe these uncertainties have limited impacts on our findings and conclusions. First, the user and producer accuracies of oil palm maps in Sumatra (containing Riau province) from Descals *et al* (2021) are lower than in other oil palm regions, with smallholder UA = 63.27% ± 7.82% and industrial PA = 69.15% ± 4.62%. Misclassifications are mostly between industrial and smallholder oil palm. The farm size of smallholder oil palm was set at 25 ha, following the official Indonesian government definition. Commission errors for smallholder oil palm and omission errors for industrial oil palm could mostly be caused by smallholder oil palm plantations greater than 25 ha. According to Jelsma *et al* (2017), some independent smallholder palm oil farms could be 200 ha or larger but still be much smaller than typical industrial oil palm estates. If we relaxed the restrictions of the smallholder farm size, the user accuracy for smallholder and producer accuracy could both be increased. We have no evidence that commission and omission errors are systematically related to our key variables (such as distance to roads, distance to mills, migrant villages, or concessions). For instance, Descals *et al* (2021) did not use spatial data on road density to map oil palm. However, optical and radar remote sensing signals used to map oil palm could be sensitive to road density and could be in part responsible for the ability of remote sensing to map oil palm.

5. Conclusions

By analyzing the spatial patterns of smallholder oil palm expansion over peat swamp forests in Riau since 1990, we found that smallholder oil palm areas had the smallest average distance to the nearest roads, mills, and big cities, compared with industrial oil palm, remaining peat swamp forests, and other land uses. But smallholder oil palm plantings averaged longer distances from mills than industrial oil palm, especially inside oil palm concessions. In addition, by examining the potential drivers of smallholder oil palm expansion, we found that increased proximity to mills and roads has significant and negative effects on forest cover, and that concessions significantly restrict smallholder oil palm expansion. Peat swamp forests have a higher likelihood of being converted into smallholder oil palm within migrant villages. Being an area of peatland with forested zones does not effectively reduce the likelihood of conversion to smallholder oil palm.

Our results provide important insights for conserving remaining peat swamp forests locally and globally. First, the high-risk areas that we identify in Riau, based on distance to roads and mills, should be given higher priorities for protection and conservation of the remaining peat swamp forest. Second, better design of the location of mills, transportation networks and government policies governing the locations and boundaries of concessions and migration settlements could be essential to slow, and even avoid, smallholder oil palm expansion into peat swamp forests. Thirdly, the enforcement of forestry law needs to be improved and monitored to conserve the remaining peat swamp forests. Further studies are needed to evaluate if these patterns hold in other provinces that are rich in peat swamp forest.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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