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Drainage density and land cover interact to affect fire occurrence in Indonesian peatlands

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Abstract

Fire occurrence in tropical peatlands is closely related to both land cover type and proximity to drainage (canal) networks. However, little is known about the extent to which land cover and drainage density interact to alter fire occurrence. Here, we assess the relationship between these variables in the peatlands of Sumatra and Kalimantan, Indonesia, spanning a five-year period of inter-annual climatic variability. Visible Infrared Imaging Radiometer Suite (VIIRS) imagery was used to map active fire hotspots. Drained peatlands experienced up to 13 times greater annual mean hotspot density (number of fire hotspots per km^2) when compared to peatlands without canals. The greatest difference in fire hotspot density between drained and undrained peatlands occurred in forested peatlands (by a factor of 2.6-13.3), followed by shrublands (1.1-7.6), crop lands (1.4-5.0) and plantations (1.2-2.6), where largest differences were found in ENSO neutral years. We found a curvilinear relationship between hotspot density and canal density, with the relationship depending on land cover and ENSO status. At low to moderate drainage density, hotspot density increased with drainage density in all land cover types in 2013-2017. Heavily drained plantations experienced a lower hotspot density than moderately drained plantations possibly due to factors such as management practices or impacts of previous fire history. The relationship with drainage density was strongest in 2013, an ENSO-neutral year, and weakest in the strong El Niño of 2015. Our findings support the critical need for fire management in

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drained tropical peat areas. Peat fire management planning and peatland restoration should be tailored to the differing responses of fire to climate variability, drainage density and land cover types.

Keywords: drainage, canal, peat fire, climate variability

1. Introduction

Peatlands cover around 4.04-4.23 M km^2 (Melton et al., 2022; Xu et al., 2018). Peat constitutes a major component of the terrestrial carbon (C) pool, storing more than 600 Gt C (Yu et al., 2010), exceeding the 383-466 Gt C stored in vegetation (Pan et al., 2011; Watson et al., 2000). Tropical peatlands store 152–350 Gt C (Gumbricht et al., 2017; Ribeiro et al., 2021). However, ecosystem disturbances can shift peatlands from a carbon sink to a source (Hirano et al., 2012; Page & Baird, 2016; Ribeiro et al., 2021; Turetsky et al., 2015).

Burning of above-ground vegetation, and of the peat, leads to release of carbon to the atmosphere. Peat fires result in global annual emissions of 244-1459 Mt CO_2eq, with the highest contributions from tropical regions, especially Equatorial Asia with intensively burned peatlands (Prosperi et al., 2020). Most peatland fires in this region occur in Indonesia, which contains 14.9 M ha of peatland (Ritung et al., 2011). Peatland fire in Indonesia resulted in annual emissions of 12.5 - 822.7 Mt CO_2eq during 2000-2019 (MoEF, 2021). The severe El Niño in 1997 resulted in extensive fires that released 2970-9423 Mt CO_2eq from peat and vegetation (Page et al., 2002), which is higher than the global annual average of carbon emissions from biomass burning (Prosperi et al., 2020). Apart from decreasing C stocks, peat fires lead to a range of undesirable outcomes, from forest loss (Adrianto et al., 2019; Hoscilo et al., 2011) to economic costs (Kiely et al., 2021). Peat fires also expose millions of people to dangerous levels of air pollution, leading to health problems and death (Hein et al., 2022; Kiely et al., 2020).

Peatlands are generally combustible in dry conditions (Hayasaka, 2023), and human actions, as well as extreme climatic events, may increase the frequency and intensity of fire (Sloan et al., 2017). Fire occurrence in Indonesian peatlands is associated with the El Niño Southern Oscillation (ENSO) (Murdiyarso & Adiningsih, 2007). The largest burn area occurs during the dry years following El Niño events, and the lowest burn area is found during La Niña years (MoEF, 2022). Furthermore, projected drier conditions under future climate change (BMKG, 2022; Li et al., 2007) may escalate fire risk.

Previous studies have analysed the interactions between land cover change and peat fire at small scale (Adrianto et al., 2019; Miettinen et al., 2017; Trancoso et al., 2022; Vetrita & Cochrane, 2019). Forested peatlands in Sumatra and Kalimantan declined in area by more than half between 1990 and 2015 (The World Bank & BPS, 2019), resulting in Indonesian peatlands becoming more vulnerable to fire. Peatland conversion is commonly accompanied by drainage infrastructure which has been extensively constructed across Indonesian peatlands (Dadap et al., 2021) and which has impacts on carbon emissions (Hirano et., 2012). Water tables deepen in response to drainage (Basuki et al., 2021; Deshmukh et al., 2021; Evans et al., 2019; Hooijer et al., 2012), resulting in drier peatland that is more prone to fire (Taufik et al., 2022; Tsuji et al., 2021). Fire frequency, burn depth and burnt area are greater closer to canals than further away (Konecny et al., 2016; Glukhova & Sirin, 2018; Prayoto et al., 2017). Rainfall and proximity to canals were key factors influencing peat fires in a 44000 ha area in Central Kalimantan studied by Medrilzam et al. (2017). Furthermore, Taufik et al. (2019) suggested that drained areas experienced fire earlier in the dry season when compared to pristine peatlands.

The scale of drainage infrastructure varies depending on human activities. Each type of crop requires a specific range of water-table level, which may also vary depending on growing stage, for optimal production. For example, sago can grow in peatlands with shallow water tables (<50 cm below ground level), while oil palm requires deeper water tables (>50 cm below ground level) (Matysek et al., 2018; Melling et al., 2005) and needs a dense drainage network. This has resulted in a complex and varied drainage system across a range of land covers. However, it remains unknown how fire occurrence varies with drainage density at a large scale under varied conditions including land cover types and climate variability. Further assessment that integrates these variables is urgently required to improve understanding of how management changes have modified fire occurrence. This assessment is critical to informing peatland and fire management policy and practice as peatland conversion is still occurring, even while some restoration work has been conducted. In this study we provide that assessment by examining the role of drainage and land cover across Sumatra and Kalimantan under a range of climate conditions characterised by ENSO.

2. Materials and Methods

2.1 Study Area

We assess relationships between drainage, landcover and fires across the peatlands of the Indonesian regions of Sumatra and Kalimantan which represent 78% of the Indonesian peatland area (Ritung et al., 2011). Peatland extents were based on the peat map produced by the Indonesian Centre for Agricultural

Land Resources Research and Development, Ministry of Agriculture (MoA) (Ritung et al., 2011), accessible via the global PeatMap by Xu et al. (2018) at https://archive.researchdata.leeds.ac.uk/251/ (accessed in July 2023).

2.2 Datasets

The fires were represented by the active fire (hotspot) products of the Visible Infrared Imaging Radiometer Suite (VIIRS), from the Fire Information for Resource Management System (FIRMS), NASA. This product has a spatial resolution of 375 m with temporal coverage starting from January 2012. Daily hotspot data were collected from https://firms.modaps.eosdis.nasa.gov/download/ (accessed in July 2023). We also analysed other fire variables, including Fire Radiative Power (FRP) from the same product and burnt area from MODIS (NASA) at https://search.earthdata.nasa.gov/search?q=C2565786756-LPCLOUD (accessed in February 2023) (Giglio et al., 2021). For climate variables, we focused on the ocean-atmosphere phenomena affecting weather conditions in Indonesia, ENSO and the IOD (Indian Ocean Dipole). The Oceanic Niño Index (ONI) and the Dipole Mode Index (DMI) are the indicators used to identify ENSO and IOD conditions based on sea surface temperature (SST) in the Pacific and the Indian Oceans. ONI is a three-month average anomaly of the extended reconstructed SST (ERSST) version 5 in the Niño-3.4 region (5^{o}N-5^{o}S, 120^{o}-170^{o}W). These data were obtained from National Centre for Environmental Prediction (NCEP), National Oceanic and Atmospheric Administration (NOAA), available at https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php (accessed in July 2023). DMI represents an anomalous SST gradient between the western equatorial Indian Ocean (50^{o}-70^{o}E and 10^{o}S-10^{o}N) and the south-eastern equatorial Indian Ocean (90^{o}-110^{o}E and 10^{o}S-0^{o}N). This index is produced by NOAA and was obtained from https://psl.noaa.gov/gcos_wgsp/Timeseries/DMI/ (accessed in July 2023). We converted DMI and hotspots into three-month average values to assess the seasonal patterns (dry and wet season) in Indonesia. Based on an 11-year period (2012-2022), we analysed the temporal and spatial distribution of hotspots and the correlation between hotspot density and ONI and DMI.

The drainage map was taken from Dadap et al. (2021) at https://purl.stanford.edu/yj761xk5815 (accessed in July 2023) and contains the canal network in 2017 for the studied areas. This product maps canals that have a width greater than 5 m and includes primary and secondary canals. Data on canal width are not available Tertiary canals (ditches) are not covered by this map; however, the map is the best up-to date option that is publicly accessible.

The land cover (LC) was identified according to a time series layer of LC maps produced by the European Space Agency (ESA) Climate Change Initiative (CCI) (Defourny et al., 2017; ESA, 2017) and a plantation map from Transparent World (2014). The layer was obtained at https://earthobs3.arcgis.com/arcgis/rest/services/ESA_CCI_Land_Cover_Time_Series/ImageServer (accessed in September 2023) and from https://data.globalforestwatch.org/datasets/gfw::tree-plantations/explore (accessed in September 2023). LC maps provide 22 LC categories with varied tree cover types, and the plantation map gives more detailed information on perennial crop types. The map consists of single and mixed perennial crops including oil palm, hevea, acacia, fruits like coconut, areca, coffee, clearing/young plantation, and others.

Based on LC classes, the Indonesian peatlands across both islands consisted of 41% Forest, 46% agricultural lands (Plantations and Other Crops), 13% Other Vegetation, and less than 0.3% settlements and water bodies. About 75% of the agricultural lands are perennial plantations, dominated by large industrial plantations (65%). Medium and small plantations contribute 8% and 12% respectively, and the rest (15%) are clearings/very young plantations. The large industrial plantations are dominated by monocultures of Oil Palm and Acacia. Medium and small plantations are dominated by mixed plantation including Oil Palm, Hevea, fruits (Coconut Palm, Areca) and monoculture plantations of Coconut Palm and Hevea

2.3 Impacts of drainage on fire

We analysed the effect of drainage on fire hotspots in Indonesian peatlands during a five-year period, 2013-2017. This period was selected to represent the typical variability of climate conditions in Indonesia affected by ENSO and IOD, involving an ENSO-neutral year (2013), dry years (an ENSO neutral-to-weak El Niño with negative IOD in 2014, and a strong El Niño with positive IOD in 2015), and wet years (La Niña and negative IOD in 2016-2017). We did not include the years after 2017 because the commencement of long-term national peatland restoration practice may have modified the drainage condition in places. We used ArcGIS Pro 3.1.4 for data analysis.

Grid cells with a resolution of 1 km for peat extent in the studied areas were produced and used as reference cells from which fire density values were calculated. We selected all cells that contain some peatland. Annual hotspot density was calculated as the sum of hotspots in each grid cell. An individual hotspot was assigned to a grid cell where the central coordinates of the hotspot fell within the border of the cell. Canal density was calculated as the total length of canal present in each cell .

Individual cells were assigned to four main LC categories modified from LC and plantation maps, 'Forests' (the undisturbed/less disturbed ecosystem); two groups of agricultural land ('Plantations' and 'Other Crops'), representing managed lands of a disturbed peat ecosystem; and 'Other Vegetation' (assumed to be unmanaged lands of a disturbed peat ecosystem). LC type is defined by the majority (>50%) of LC within each cell, and heterogeneous cells or those with no dominant land cover (3% of total cells), are excluded from analysis. All cells overlapping with the plantation map were assigned as Plantations. Other LC types were classified based on the ESA LC map. Assigned cells for tree cover were grouped into Forests. Assigned cells for crops but not overlapping with the plantation map were grouped as Other Crops (assumed to be seasonal crops). The rest of the cells overlapping with shrub, herbaceous, grassland and mixed vegetated cells with tree cover or agricultural lands less than 50%, were grouped into Other Vegetation. We excluded cells from our analysis that were not assigned to the above four classes, such as urban areas and water bodies. LC change is often associated with drainage construction as well as fire which is used to clear vegetation (Adrianto et al., 2019). To exclude these effects we only selected areas where LC remained the same throughout the study period (2013-2017), which accounts for 10.7 M ha (94% of Indonesian peatlands in Sumatra and Kalimantan). Data on drainage extent is only available for 2017 and we assume a constant drainage network during the study period.

We overlaid the grid cells containing hotspot and canal density information with the LC map. The individual cells were grouped based on canal density value, ranked from low to high, into bins containing 500 data points for every LC class. The mean values of the groups were used for further analysis. We applied data grouping to help capture the overall interaction between canals and hotspot density because the hotspot density data are skewed, with 80-99% of grid cells having zero annual hotspots.We used Analysis of Variance (ANOVA) to determine whether there were significant differences in hotspot density between undrained and drained peatlands, and also across different types of LC. We then plotted the distribution of the canal density and annual average hotspot density at a national level. The same analysis was also applied at a provincial level to examine regional variability. We selected two provinces where most peatlands are located and which also represent different seasonal patterns and peat conditions: Riau province with more drained peatlands, and Central Kalimantan province where undrained peatlands dominate. We used multiple regression to examine the effect of canal density, LC and ENSO on hotspot density. We identified LC and ENSO status using dummy variables (with Forest and the ENSO-neutral year as the default). There are three models we applied with hotspot density as a dependent variable. The independent variable of the first model was ENSO status. The second model used ENSO status and LC type. Lastly we applied ENSO status, LC type and canal density with a quadratic function to fit the apparent curvilinear relationship we found graphically between hotspot density and canal density.

3 Results

3.1 Ecosystem conditions of Indonesian peatlands

During 2013-2017, fire hotspots occurred in 38% of the study area (Figure 1b). Over half (53%) of areas with hotspots were agricultural lands, with a dominance of Plantations (Table S1). There were 632,012 hotspots recorded in the study area (2013-2017) with a large inter-annual variation. An ENSO-neutral year (2013) experienced 91,075 hotspots, which increased to 209,560 in 2014 (weak El Niño), and to 309,514 in 2015 (prolonged drought due to strong El Niño combined with a positive IOD). The number of hotspots was lower in 2016 and 2017 when La Niña occurred, with 16,440 and 5,423 hotspots respectively. Based on Pearson's correlation, the number of dry season (July to November in 2012-2022) hotspots in Indonesian peatlands is greatly affected by ONI (r=0.87) and moderately influenced by DMI (r=0.52).

As shown in Figure 1c, 76% of peatlands in Sumatra had canals compared to 42% in Kalimantan. Most drained peatlands (91%) had a canal density below 3.3 km km^{-2} and 55% of drained peatland had a canal density below 1.6 km km^{-2}. The distribution of canal densities varied in each LC (Figure 1a and Figure 1d). Most forested peatlands (79%) had no canals. Meanwhile, more that 92% of Plantations were drained with a canal density up to 10.6 km km^{-2}. Other Crops and Other Vegetation were drained in 72% and 64% of the area and canal density ranged up to 8.2 km km^{-2} in both LCs.

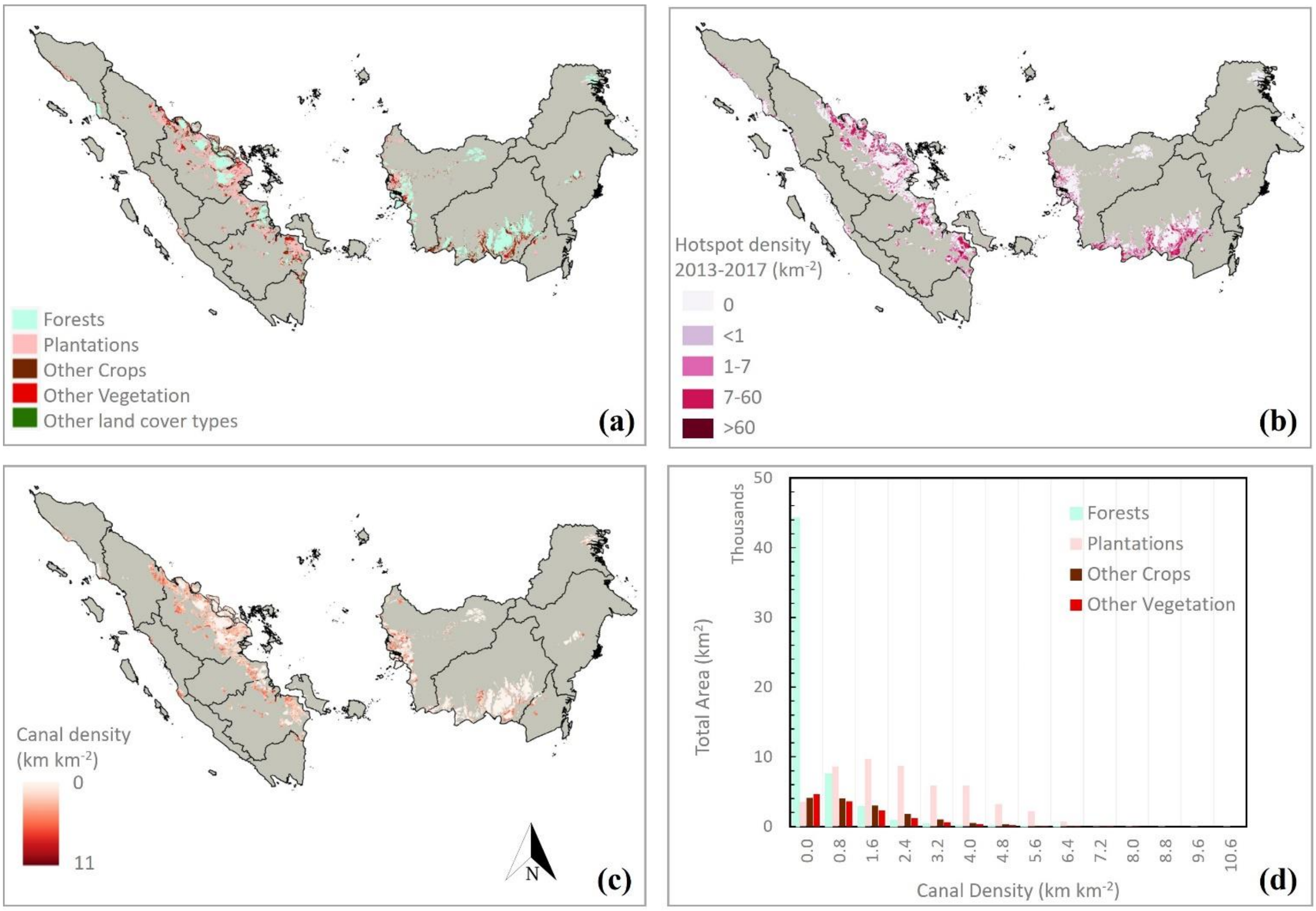

Figure 1. Peatland extent and condition in Sumatra and Kalimantan: (a) land cover map of peatland within the study area; (b) hotspot density in a five-year period (2013-2017); (c) drainage density in study area; (d) area of land cover categories classified by drainage density; bins are equidistant with labels rounded to the nearest tenth of a km km^{-2}.

3.2 The implications of climate, drainage, and land cover on peat fire

Peatlands with canals had a greater hotspot density than undrained peatlands ($p < 0.001$), with the largest difference in the ENSO-neutral year. In this year, median hotspot density in undrained peatlands was 0.08 km^{-2} but was approximately 13 times greater in drained peatlands at 1.06 km^{-2} (Figure 2). During the weak El Niño, median hotspot density was 0.35 km^{-2} in undrained peatlands but 6.3 times higher (2.20 km^{-2}) in drained peatlands. The drought continued to the next year with a stronger El Niño, leading to drained peatlands having the highest hotspot densities with a median of 2.34 km^{-2}, about two times higher than for undrained peatlands (1.13 km^{-2}). Hotspot density in undrained peatlands in 2015 was similar to hotspot density in drained peatlands during the ENSO-neutral year in 2013. The number of hotspots was much smaller during La Niña, when median hotspot density in undrained peatlands was 0.03 km^{-2}and 0.15 km^{-2} in drained peatlands in 2016. Despite the impact of La Niña and a negative IOD, drained peatlands still had almost double the hotspot density compared to undrained peatlands during the ENSO-neutral year. Hotspots further decreased in 2017 as La Niña continued, with a median density of 0.01 km^{-2} and 0.05 km^{-2} in undrained and drained peatlands, respectively.

There are differences in hotspot density at regional (province) level linked to differences in climate (Figure S1). Riau has a large area of drained peatlands (76% drained) and had an average hotspot density in 2013 of 1.5 km^{-2}, seven times higher than in Central Kalimantan (33% drained) with 0.21 km^{-2}. In 2014, hotspot density in Riau and Central Kalimantan increased to 2.1 km^{-2} and 1.2 km^{-2} respectively. In 2015, hotspot density in Riau dropped to 0.5 km^{-2} whereas it increased to 3.1 km^{-2} in Central Kalimantan.

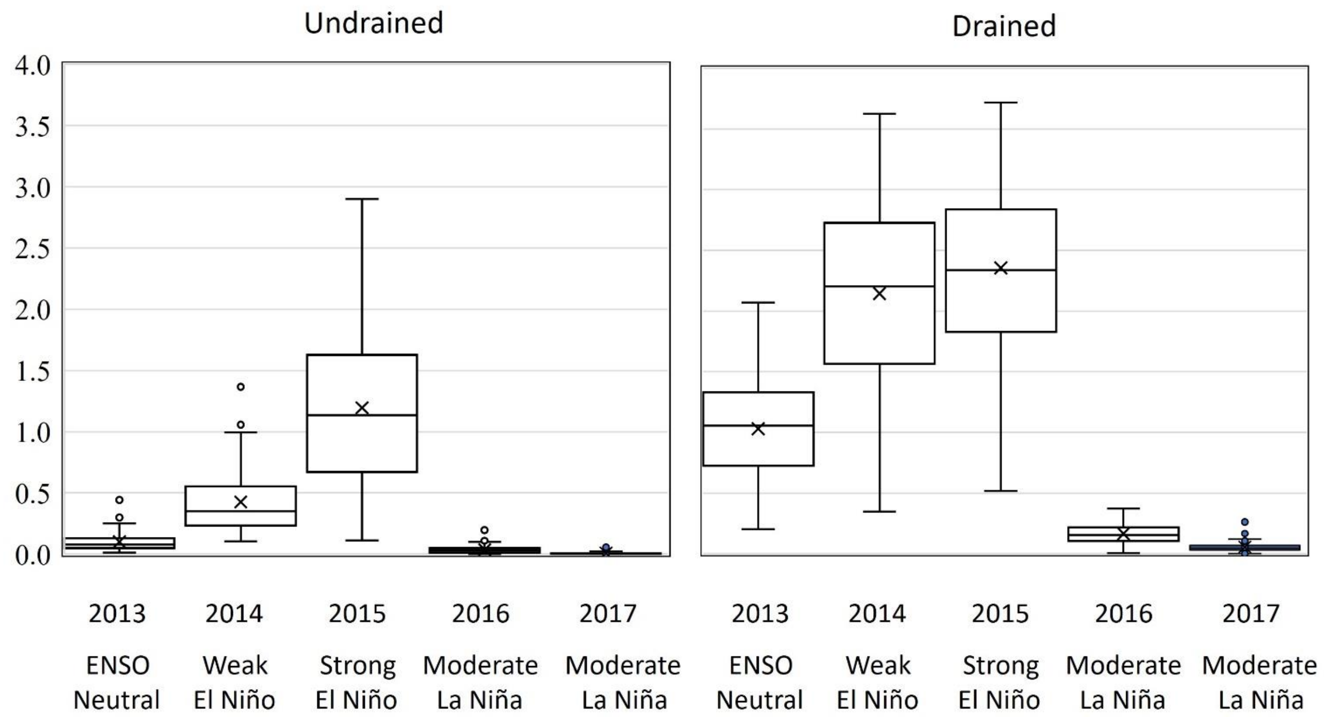

Figure 2. Annual hotspot density (km^{-2}) in undrained and drained Indonesian peatland (Sumatra and Kalimantan) during 2013-2017. The box shows the quartiles of the data distributed from lower (bottom edge) to upper (top edge) with the horizontal line splitting the box as the median and the x sign as the mean; the vertical line shows the range of data from lower (Q1-1.5*IQR) to upper values (Q3+1.5*IQR); the points show outliers).

Hotspot density is also shaped by the type of LC. Overall, forested peatlands had the lowest mean hotspot density with 0.34 km^{-2} compared to other LCs during the period of study ($p<0.001$) (Table 1). In the ENSO-neutral year, the mean hotspot density in Forests was only 0.04 km^{-2}, while Plantations, Other Vegetation and Other Crops had 5.6, 8.6 and 10 times that hotspot density respectively. The relative differences in hotspot density were lower in subsequent years when El Niño and La Niña occurred. We also compared the hotspot density between undrained and drained peatlands for each LC (Table 1). We found denser hotspots in drained peatlands when compared to undrained peatlands for all categories of LC.

In Plantations, hotspot density also varies with type of plantations (Table S4). Recently cleared lands and oil palm plantation experienced higher hotspot density (2.5km^{-2} and 1km^{-2} respectively) than other plantation (timber, fruit, and others) in 2013. ENSO events in 2014 and 2015 increased the hotspot density in almost all of the plantation area, with the largest increases in timber plantation (345% and 865%) and the lowest in oil palm plantation (62% and 26%). On the other hand, hotspot density in cleared lands increased by 82% in 2014 but then decreased by 42% in 2015, unlike other plantations.

Table 1. Mean hotspot density based on land cover types in Indonesian peatlands. U is undrained peatland with no canal, and D is drained peatland (canal density > 0 km km^{-2}).

Land cover type	Mean hotspot density (km^{-2})											
	2013		2014		2015		2016		2017		All years	
	U	D	U	D	U	D	U	D	U	D	U	D
Forest	0.04	0.51	0.23	1.47	0.75	1.93	0.02	0.11	0.01	0.06	0.21	0.82
Plantation	0.32	0.81	0.67	1.67	1.05	1.71	0.04	0.10	0.02	0.02	0.42	0.87
Other Crops	0.37	1.66	1.44	3.52	3.19	4.48	0.15	0.34	0.02	0.07	1.03	2.05
Other Vegetation	0.26	1.71	1.13	3.59	3.43	3.67	0.11	0.31	0.02	0.18	0.99	1.89

There was a curvilinear relationship for data from 2013-2017 between hotspot density and canal density, with a peak in hotspot density at a canal density of around 1-3 km km^{-2} (Figure 3), with the peak varying between LC types and ENSO status. Peatlands with a very dense drainage network, mostly in Plantations, had a gradual decrease of hotspot density as drainage density became very high. In 2013, canal densities strongly influenced the density of hotspots with r values of 0.97, 0.96, 0.94, and 0.67 in Forests, Other Vegetation, Other Crops and Plantations respectively. The increase in hotspot density with drainage density varied strongly with LC, with the lowest hotpsot density in Forests and highest in Other Crops and Other Vegetation. However, the El Niño events in the proceeding years weakened the impact of drainage density on hotspots, especially in 2015 as hotspots spread to undrained areas. The r values decreased to 0.75, 0.43, 0.57, and 0.58 in Forests, Other Vegetation, Other Crops and Plantations respectively.

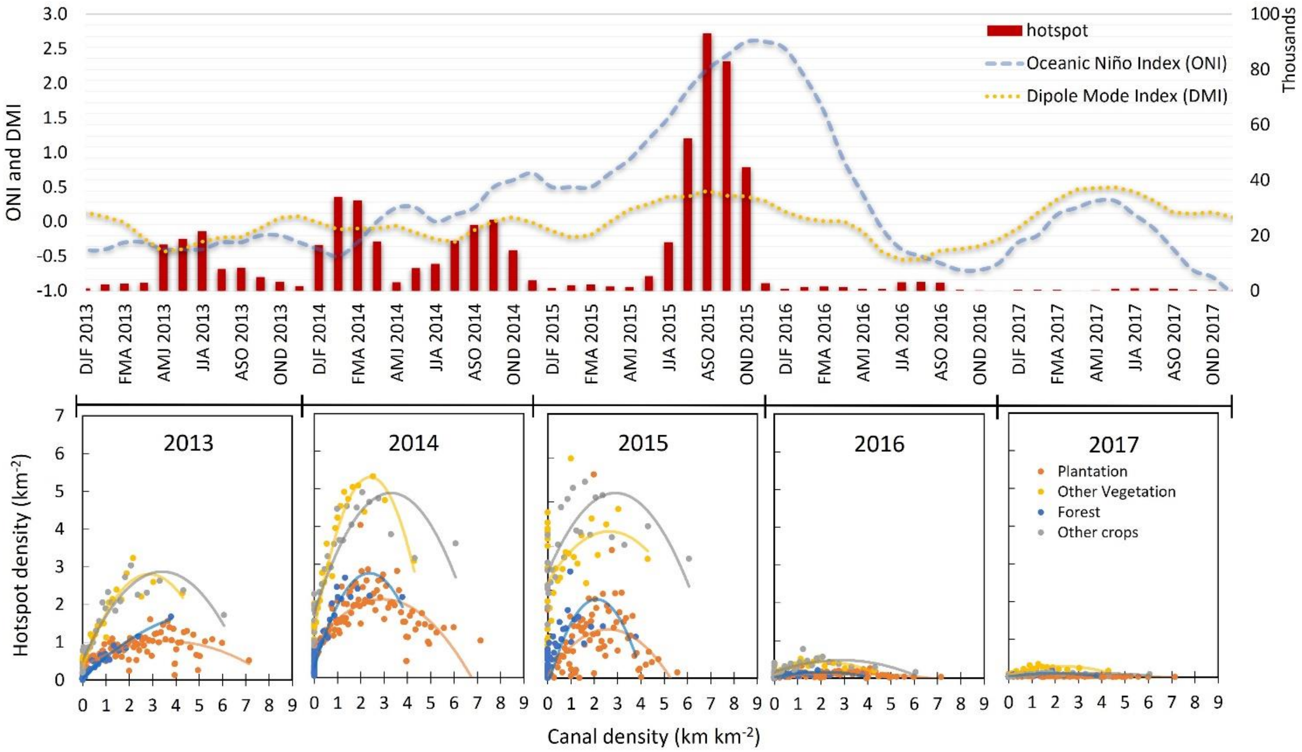

Figure 3. Relationships between fire hotspots, climate, land cover and drainage during 2013 to 2017. Top: three-monthly running mean of total hotspots detected in Indonesian peatlands, the Oceanic Niño Index (ONI), and the Dipole Mode Index (DMI); Bottom: scatter plots of hotspot density (km^{-2}) as a function of canal density ($km\ km^{-2}$) for different land cover classes.

The regression analysis showed that climate condition associated with ENSO partly explained the hotspot density with $r^2 = 0.40$ (Table S2). Adding LC as a categorical variable in a multiple regression increased r^2 to 0.59, while multiple regression combining the information on climate condition, LC classification and drainage density, resulted in $r^2 = 0.67$ (Figure S2). All predictors significantly influenced hotspot density (p<0.001), except for Plantation (p=0.25) (Table S3). Multicollinearity tests between the variables (climate, LC and drainage) showed the variance inflation factor and tolerance are lower than 5 and higher than 0.1 to 0.2, respectively, for all variables (Table S3).

We also compared hotspots with other fire indicators, including FRP and burnt area. Hotspot density is strongly correlated with FRP (r=0.95) and burnt area (r=0.87). However, increased fire occurrence does not necessarily lead to a larger burnt area, especially in the strong El Niño in 2015 (Figure S3). Both FRP and burnt area had a strong positive relationship with drainage density in 2013 (Figure S3). The influence of drainage density weakened in the years following El Niño.

4 Discussion and Conclusion

Our study shows the influence of drainage density on the occurrence of fire hotspots, while highlighting its interaction with land cover and climate variability. These findings expand the scope of existing research on how drainage infrastructure exacerbates fire risks in peatlands with different behaviour under varying environmental conditions. The dry period following the positive anomaly of SST in the Pacific causes increases in Indonesian peatland fire activity (Murdiyarso & Adiningsih, 2007). Spatially, fire occurrence in each LC type behaves differently in response to drainage and ENSO status. Higher hotspot densities are found in areas associated with human activities (deforested and drained). We found a positive relationship between canal and hotspot density up to moderate drainage density, as found in 91% of the study area in 2013. This relationship weakened especially during the strong El Niño in 2015, when drought extended to wider areas from the canals (Lu et al., 2021).

For areas of high canal density which are dominated by Plantations, hotspot density tended to decline as canal density increased. This may seem counterintuitive as heavily-drained peatlands are associated with deeper water tables (Hirano et al., 2015), and a higher combustion risk (Hayasaka et al., 2016; Khakim et al., 2022). However, the pattern may be related several factors that need to be investigated further. First, both land management and land ownership could be important . In our study area, the large industrial plantations had the highest canal density with a mean of 2.8 km km^{-2}, compared to 1.8 km km^{-2} and 1.4 km km^{-2} for medium and small plantations. The large, industrial-scale perennial plantations may have more income and resources (BPS, 2021) for pro-active fire management. Additionally, there are several regulations related to fire preventive policy, such as a zero-burning policy and the Regulation (PP) No.71/2014, to maintain land use permits. Most of Plantation in the studied area (63%) is oil palm plantation. According to Prayoto et al., (2017), registered large-scale oil palm companies tend to follow zero-burning policy compared with unregistered companies. Also, the recently-cleared plantations show a decrease in hotspot density in 2015, which may indicate the contribution of land management (Sloan et al., 2022). We observed different behaviour in the different plantation types. Our results show that timber plantation, which make up 25% of plantations and have a lower mean canal density than oil palm plantation, experienced an increase in hotspot density of more than 8-fold between 2013 and 2015, because these areas are more prone to the effect of ENSO (Stolle & Lambin, 2003). Another point to consider is the high density of canals may limit the spread of fire, especially smoldering fire, to spread, through acting as fire breaks. According to Catau et al., (2016), most of fires ignited in oil palm plantations stayed in their boundary, while fires started in degraded areas tend to escape. Lastly, peat loss has potentially occurred in densely drained peatlands due to oxidation and repeat burning (Page & Hooijer, 2016), especially in plantations with shallow peat layers as suggested in the Regulation (PP) No.71/2014. Peatlands used for plantations experience intense subsidence (Evans et al., 2019; Deshmukh et al., 2021; Hooijer et al., 2012; Nagano et al., 2013). Also, according to Konecny et., (2016), the consumption of peat fuel decreases with each successive fire event. This means that densely drained peatlands may become less prone to fire since the peat has already burned in previous fire events or decomposed and has been lost to the atmosphere, and the peat sruface may move closer to the water table. Our study focuses on the impacts of LC, but fire during land cover changes or land clearing (Saharjo et al., 2005; Adrianto et al., 2020; Trancoso 2022) was not included. Overall, our analysis does not suggest that additional drainage reduces fire risk, rather that active management is likely much more intense in heavily drained plantations, but this may vary with management practice.

For peatlands outside of the Plantations LC, the positive relationship between drainage density and hotspot density appears stronger especially in 2013-2014, with the slope of the relationship varying by LC. Forests experience the fewest fire hotspots. These areas tend to have a shallower water table (Deshmukh et al., 2021), which may reduce peat fire susceptibility (Taufik et al., 2020). Forest canopy and understorey affect the near-surface microclimate, leading to higher fine fuel moisture content and fewer days when fuels are predicted to be available for burning (Pickering et al., 2021). Other Crops and Other Vegetation had the greatest hotspot density, and these land covers are where Cattau et al. (2016) previously found that 52% of fire ignition occurred for Central Kalimantan. The area covered by Other Crops tends to be managed for seasonal crops by smallholders who have less capability (BPS, 2022) to control fire compared to managers of sites in the Plantations category. About 71% of Indonesian farmers operate at small-scale (owning crop land less than 2 ha) with the lowest income in the agricultural sector (BPS, 2022). Furthermore, for many smallholders, fire is one of the tools commonly used in agricultural activities: for land preparation and biomass clearing after harvesting (Merten et al., 2021; Medrilzam et al., 2017; Winarno et al., 2020). As seasonal crops have a short growing period of 2-6 months (BRG & BPPLHK, 2019), there may be more frequent agricultural activities involving fire. In these landscapes a combination of interventions with communities may be needed to reduce fire (Carmenta et al., 2021). Other Vegetation had a high hotspot density, slightly lower than Other Crops. These areas have less canopy cover, in the form of shrubs, grassland and mixed vegetation, and include abandoned agricultural lands (Medrilzam et al., 2017) with limited perceived economic value. Reforestation and improvement of the hydrological condition (rewetting) of such areas may reduce fire risk (Murdiyarso et al., 2021).

There are important differences in hotspot density at the regional level linked to ENSO (Figure S1). In 2015, hotspot density in Riau dropped whereas it increased in Central Kalimantan, as the impact of El

Niño on drought is more pronounced in Central Kalimantan compared to Riau (Fanin and Van Der Werf (2017). About half of plantations are located in Riau; this may explain the lower increase in hotspot density in Plantation between 2014 and 2015 when compared to other LCs (Table 1).

Our study provides valuable insights into how fire density varies with density of drainage across LC and climate state in Indonesian peatlands. Deforested and drained peatlands are at a high risk of fire especially during ENSO-neutral to strong El Niño events. Hotspot density increases with canal density, with a strong correlation in 2013. El Niño events diminish the impact of canal density, especially during the prolonged drought in the strong El Nino of 2015, when relationships show moderate correlation outside Forests. Our results support the strategy of peat protection in Indonesia, including suspending further peat forest conversion, continuing reforestation of deforested peatlands, rewetting drained peatlands (BRGM, 2021), as well as increasing peat fire management and local awareness. There are a number of areas that need further research. The findings of this study are limited to the primary and secondary canal network due to data availability. Excluding tertiary canals will underestimate drainage density. Future research using finer resolution drainage data could be useful. Hotspot data only indicate surface fire occurrences but not fire severity or whether fire burns into the peat. Future work is also needed to assess the effects of peatland restoration activities (Budiningsih et al., 2024) including on reducing fire events and associated impacts.

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Data Availability Statement

All datasets used in this paper are publicly available, licensed under CC BY 4.0, CC BY 3.0 and ESA CCI. PeatMap and drainage network map are from Xu et al. (2018) (https://archive.researchdata.leeds.ac.uk/251/) and Dadap et al. (2021) (https://purl.stanford.edu/yj761xk5815). Daily hotspots were from FIRMS NASA (https://firms.modaps.eosdis.nasa.gov/download/). Land cover and plantation maps were from ESA (https://www.arcgis.com/home/item.html?id=1453082255024699af55c960bc3dc1fe) and Transparent World (https://data.globalforestwatch.org/datasets/gfw::tree-plantations/explore).

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