Discover the Relationships Between Fire Hotspot, Land Use and Land Cover in Riau Province, Indonesia.

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Abstract

Forest and peatland fires occur regularly across Indonesia, resulting in large greenhouse gas emissions and causing major air quality issues. Over the last few decades, Indonesia has also experienced extensive forest loss and conversion of natural forest to oil palm and timber plantations. Here we used data on fire hotspots and tree-cover loss, as well as information on the extent of peat land, protected areas, and concessions to explore spatial and temporal relationships among forest, forest loss, and fire frequency. Also, we combined a new land-cover dataset with satellite data on the timing and location of fires to make the first detailed assessment of the association of fire with specific land-cover transitions. We focus on the Riau Province in Central Sumatra, one of the most active regions of fire in Indonesia.

We find strong relationships between forest loss and fire at the local scale. Regions with forest loss experienced six times as many fire hotspots compared to regions with no forest loss. Forest loss and maximum fire frequency occurred within the same year, or one year apart, in 70% of the 1 km^2 cells experiencing both forest loss and fire. Frequency of fire was lower both before and after forest loss, suggesting that most fire is associated with the forest loss process. On peat soils, fire frequency was a factor 10 to 100 lower in protected areas and natural forest logging concessions compared to oil palm and wood fiber (timber) concessions. Areas that did not change land cover exhibit lower fire frequency, with shrub (0.06 km^{-2} yr^{-1}) exhibiting a frequency of fire >60 times the frequency of fire in primary forest.

Our analysis demonstrates that in Riau, fire is closely connected to land-cover change, and that the majority of fire is associated with the transition of secondary forest to shrub and plantation. Reducing the frequency of fire in Riau will require enhanced protection of secondary forests and restoration of shrub to natural forest. During times of high fire risk, fire suppression resources should be targeted to regions that are experiencing recent forest loss, as these regions are most likely to experience fire.

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Preface

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List of Abbreviations

AATHP : Agreement on Transboundary Haze Pollution

APL : *Areal Penggunaan Lain* / Land allocated for other purposes (also known as non-forest area)

Bappenas : *Badan Perencanaan Pembangunan Nasional* / The Ministry of National Development Planning, Republic of Indonesia

BPS : Badan Pusat Statistik / Statistics Indonesia, Republic of Indonesia

BRG : *Badan Restorasi Gambut* / Peat Restoration Agency

Dishut : Dinas Kehutanan / Provincial Forestry Service

DT : Decision Tree

ENSO : El Niño-Southern Oscillation

FRP : Fire Radiative Power

GFC : Global Forest Change

GFED : Global Fire Emissions Database

GLM : Generalized Linear Model

GWR : Geographically Weighted Regression

HGU : *Hak Guna Usaha* / Business Use Right

HP : *Hutan Produksi /* Production forest

HPH : *Hak Pengusahaan Hutan* / Forest Concession

HPHH : *Hak Pemungutan Hasil Hutan* / Forest Product Harvest Concession

HPK : *Hutan Produksi yang dapat dikonversi /* Convertible production forest

HPT : *Hutan Produksi Terbatas* / Limited production forest

HTI : *Hutan Tanaman Industri* / Industrial Timber Plantation

Inpres : *Instruksi Presiden* / Presidential Instruction

IOD : Indian Ocean Dipole

IUPHHK-HA: *Izin Usaha Pemanfaatan Hasil Hutan Kayu dalam Hutan Alam* / Business Permit to Utilize Timber Forest Products in Natural Forest

IUPHHK-HTI :*Izin Usaha Pemanfaatan Hasil Hutan Kayu dalam Hutan Tanaman Industri /* Business Permit for Primary Industry of Forest Products in Industrial Plantation Forest

KHG : *Kesatuan Hidrologis Gambut* / Peatland hydrological unity

LM : Linear Model

LULCC : Land use and land cover change

MIR	: Middle Infrared
MODIS	: Moderate Resolution Imaging Spectroradiometer
MoEF	: Ministry of Environment and Forestry, Republic of Indonesia
MoF	: Ministry of Forestry, Republic of Indonesia
NDVI	:Normalized Difference Vegetation Index
NFI	: National Forest Inventory
PA	: Protected Area
PP	: *Peraturan Pemerintah /* Government Regulation
RF	: Random Forest
RSPO	: The Roundtable on Sustainable Palm Oil
SVM	: Support Vector Machine
TGHK	: *Tata Guna Hutan Kesepakatan* / Forest Land Use Concession
TNNP	: Tesso Nilo National Park
UNEP	: The United Nations Environment Programme
UU	: *Undang-Undang* /Act
VI	: Vegetation Index

List of terminology

Deforestation : the replacement of natural forest by non-forestry-related land uses

Hak Pengusahaan Hutan (HPH) / Forest Concession : is a limited right of forestry undertaking in forest area, covering activities of cutting trees, reforestation, processing, and marketing of forest products.

Hutan / Forest : is an ecosystem unit in the form of a landscape containing biological resources dominated by trees, which is inseparable from its surroundings.

Hutan Adat / Customary forest : is state-owned forest located within teritory of a community adhering a customary law system.

Hutan Konservasi / Conservation forest : is a forest area with particular characters, designated mainly to preserve biodiversity and its ecosystem; consists of nature reserve area, nature conservation area, and game reserve.

Hutan Lindung / protection forest : is a forest area designated mainly to protect life-supporting systems that regulate water system, prevents floods, controls erosion, prevents sea water intrusion and maintains soil fertility; and conservation forests are those with specific attributes functioning to preserve biodiversity and its ecosystem.

Hutan Negara / state-owned forest : is forest located on the state-owned land with no concession right and land title.

Hutan Produksi / Production forest : is a forest area designated to produce forest products, and can consist of permanent production forest, limited production forest, convertible production forest.

Hutan Produksi Terbatas (HPT) / Limited production forest : is forest area with certain class of slope, soil type, rainfall which has score between 125-174, outside protected forest and conservation forest.

Hutan Produksi Tetap / Permanent production forest : is a forest area with certain class of slope, soil type, rainfall which has a score under 125, outside protected forest and conservation forest.

Hutan Produksi yang dapat dikonversi (HPK)/ Convertible production forest : is production forest area which is allocated for development of non-forestry purpose.

Hutan Tetap / Permanent forest : is an area that will be permanently maintained as forest area, consists of conservation forest, protected forest, limited production forest and permanent production forest.

Indonesian Forest : is an area with a minimum mapping unit of 0.25 ha that is covered by trees higher than 5 m with a canopy cover of more than 30% (MoF).

Intact forest : consists of native tree species where there are no clearly visible indications of human activities (MoF 1989) and the ecological processes are not significantly disturbed (FAO 2006).

Intact Forest Landscape : unbroken expanse of natural ecosystems within areas of current forest extent, without signs of significant human activity, and having an area of at least 500 km2 (Potapov, et al. 2008).

Intact primary forests : have no detectable signs of human-caused alteration or fragmentation

Izin Pemanfaatan Kayu (IPK) / Timber utilization permit : is the permit to extract the timber from a relinquishment forest area for Non-forestry development

Izin Usaha Pemanfaatan Hasil Hutan Kayu dalam Hutan Alam (IUPHHK-HA) / Business Permit to Utilize Timber Forest Products in Natural Forest : is the business permit granted to use timber forest products at natural forest in production forest through cropping, cultivation, conservancy, security, and marketing.

Izin Usaha Pemanfaatan Hasil Hutan Kayu dalam Hutan Tanaman Industri (IUPHHK-HTI) / Business Permit for Primary Industry of Forest Products in Industrial Plantation Forest : is business permit granted to use timber forest products at plantation forest in production forest through land preparation, nursery,cultivation, conservation, cropping and marketing.

Kawasan Hutan / Forest Area : is a particular area which is designated and gazetted by the government as an area with permanent forest.

Kawasan hutan pelestarian alam / Nature conservation forest area : is forest area with a unique character, mainly to protect life supporting systems, preserve biodiversity, and sustainable use of biological resources and ecosystems; consists of national park, grand forest park, and nature recreation park.

Kawasan hutan suaka alam / Nature reserve forest area : is forest area with a unique character, mainly to preserve biodiversity and related ecosystems, as well as an area for life supporting systems; consists of nature reserve and wildlife sanctuary.

Pelepasan kawasan hutan / Relinquishment forest area : is the change of the status of convertible production forest into non forest area.

Perubahan fungsi kawasan hutan / Forest function change : is the change of the partial/whole status and function of a particular forest area into other status or function.

Primary degraded forests : primary forests that have been fragmented or subjected to forest utilization, for example, by selective logging or other human disturbances that have led to partial canopy loss and altered forest composition and structure

Primary forest : mature natural forests of 5 ha or more in extent that retain their natural composition and structure, and have not been completely cleared and re-planted in recent history, including both intact and degraded type

Taman buru / Game reserve : is a reserve designated for wildlife hunting

Tukar menukar kawasan hutan / Forest swap : is forest being swapped between forest areas and non-forest areas, whereby the status of production forest (HP) and/or limited production forest (HPT) is being changed into non forest area, followed by the inclusion of a non-forest area into forest area.

Chapter 1
Introduction

Fire is a significant force in shaping our environment and preserving biodiversity, but when fire regimes are changed they can lead to social, economic and environmental damages. Tropical forests in Indonesia do not burn naturally, however the increasing disturbance by humans give rise to fire. Fires tend to be concentrated in agricultural / forestry concessions and peatlands in Indonesia. Forest degradation also results in more tree spacing, allowing sunlight to reach the forest floor which encourages the growth of brush. Excessive log extraction will reduce tree transpiration power, and influences forest hydrology. In peatland, canals have been constructed to transport logging products and drain the land for commercial plantations. During prolonged periods with low precipitation, abundant fuel from dry brushes and non-moist soil create a suitable condition for fire. At the end of dry season or early wet season, some people also use fire to convert the brush, which was formerly forest, into agricultural land or plantations. Also, there are some cases where fires are used as a tool to eliminate pests and diseases from plants.

Since fire and deforestation have direct interactions, understanding the relationship between them is very important. Although many studies demonstrate that fire and land-cover change are closely linked, there is still limited information on the spatial and temporal relationship between fire and land-cover change for peatland regions of Indonesia. Specifically, there have been no detailed studies of how tree cover loss and fire frequency are related spatially and temporally across different land-cover and land-use types. This thesis focuses on the analysis of hotspot dynamics related to tree cover loss for peat and mineral soils with a range of land-use types in Riau province, Sumatra, one of the most active fire regions in Indonesia. My aim is to explore the spatial and temporal connections between fire and tree cover loss, providing new information to help forest management, peat restoration, and fire suppression efforts.

The next sections of this chapter will cover general concepts about fire hotspots and land use / land cover change such as :

1. Fire in the Earth System
2. Tropical forests and tropical peatlands
3. Fire in Indonesia

4. Causes of Fire in Indonesia
5. Fire in Riau
6. Fire in Peatlands

This chapter also covers a review of the relationships between forest fire, land use and land cover. The chapter describes the research questions and objectives. The last section describes the thesis structure.

1.1 Fire in the Earth System

1.1.1 The definition of fire

Torero (2013) defines fire as “the uncontrolled chemical oxidation of organic fuels that is generally associated with destruction”. Vegetation fires are started when a high-temperature heat source breaks down the cellulose molecule in the plant material and produces gaseous components such as methane (CH_4) which when mixed with atmospheric oxygen may initiate combustion (Scott et al., 2014).

Figure 1.1 shows the interaction between different components of fire at different scales. At the smallest scale, fuel, oxygen and heat (known as the fire triangle) ignited by a spark sets off a fast combustion called fire (Pyne, 2019). Natural ignition sources include falling rocks, volcanic discharges, extraterresterial impacts and lightning. Countryman (1972) defines the fire environment as "the conditions, influences, and modifiying forces that control the fire behaviour" and stated at a broader scale that wildland fires vary according to topography, fuel and weather. At wider spatial and temporal scales, Moritz et al. (2005) mentioned “the fire regime of an ecosystem is the collective outcome of multiple drivers, such as ignition patterns, climate, and vegetation characteristics”.

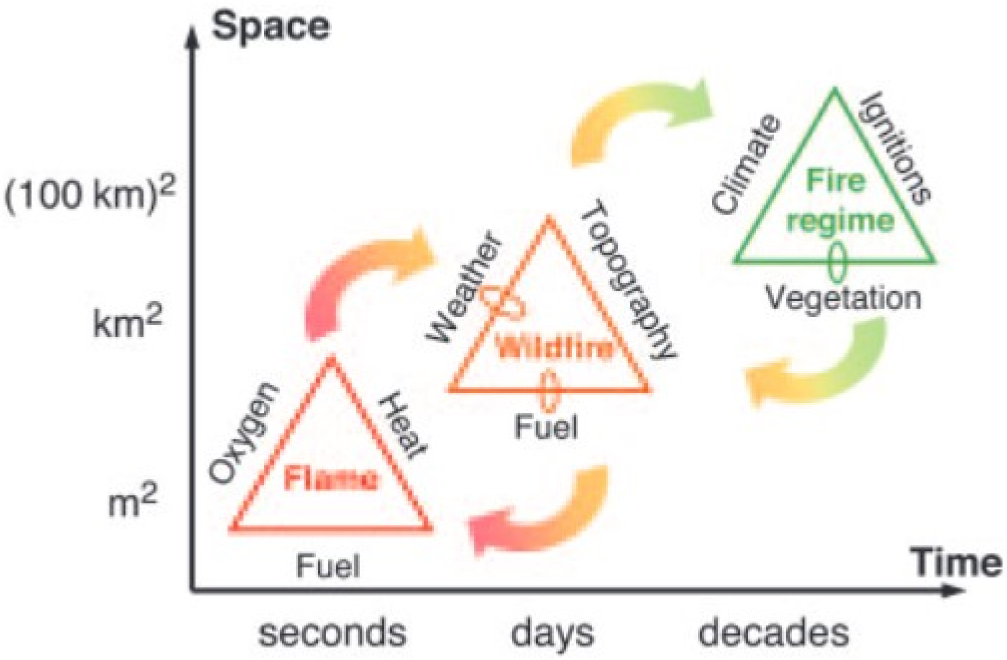


Figure 1.1 Fire at different scales (Moritz et al., 2005). Small loops show the feedback that fire has on the controls themselves, and arrows indicate feedbacks between processes at different scales.

Humans have been using fire since the Pleistocene era (James et al., 1989). In early times, humans used fire by control over ignition, then evolved to control over fuels and since 150 years ago widely substitute biomass fuels with fossil fuels. Today, fire interacts with human environmental concerns in terms of catastrophes, carbon and climate (Goldammer, 2013).

Wildfire**,** also called wildland fire is defined as “uncontrolled fire in a forest, grassland, brushland, or land sown to crops” (Britannica). The Decree of the Director General of Forest Protection and Nature Conservation, Ministry of Forestry, Republic of Indonesia Number 244 Year 1994 on Technical Guidelines for Combating Forest Fires mentions three basic types of wildfires, illustrated in Figure 1.2:

a. Surface fire, “a fire that burns surface litter, other loose debris of the forest floor and small vegetation”.
b. Crown fires, “a fire that advances from top to top of trees or shrubs more of less independently of the surface fire”.
c. Ground fires, “a fire that consumes the organic material beneath the surface litter of the forest floor”.

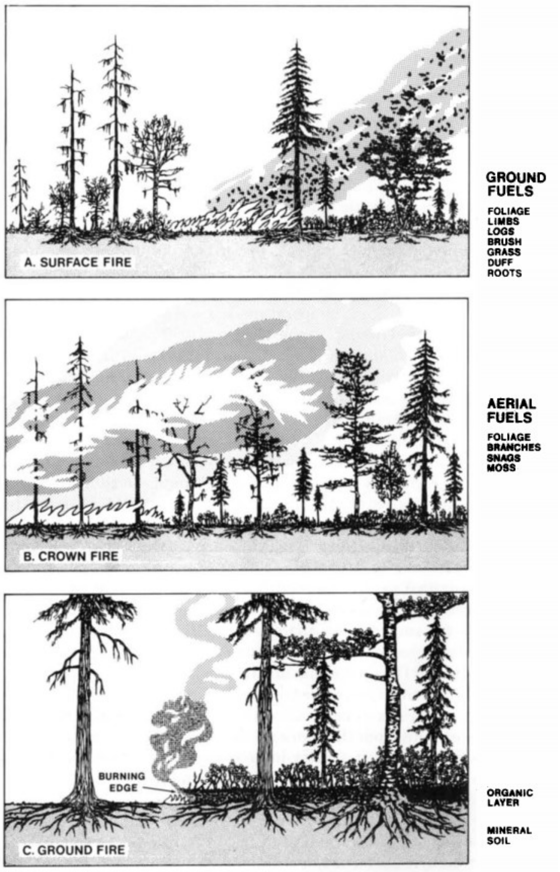


Figure 1.2 Wildfire Types (Scott, 1989 modified from Davis, 1959)

The manual book to forest and peatland fire control (Adinugroho et al., 2005) describes the jumping fire, which occurrs as a result of fire leaping from the burning area to a new area. Jumping fires make fire fighting more complicated (BBC, 2019) and some companies cited them as the cause of the fires in their concession (Anggoro, 2016).

1.1.2 Spatial and temporal patterns of fire

Wildfires began 420 million years ago as atmospheric oxygen concentration rose above 13%, while humans started using fire for domestic routines around 50-100 thousand years ago and fire related to industrial combustion has been increasing since 100 years ago (Figure 1.3).

It is estimated that an average of 608 Mha yr^{-1} burned at the end of the 20th century, not including agricultural fires (Mouillot and Field, 2005). Fires occur on every continent except Antarctica (Figure 1.4). Generally, fires are absent at very high latitudes near the poles, increasing towards the tropics. In the 1990's, 522 Mha yr^{-1} of fire occured in the tropical savannas and grassland, equivalent to 86% of global fire.The area burned by fire was greatest in Africa (55.7%), followed by South America (15.5%), Australia (9.5%) and South Asia

(6.2%). Although tropical forest fires represent only 11% of yearly burned area, they involve more biomass and so result in larger emissions of carbon (Mouillot and Field, 2005). Since the 1970s the center of forest fire activity has switched to those regions with continuing pressure from deforestation (Mouillot and Field, 2005).

Due to agricultural expansion and intensification, global burned area declined nearly 25% between 1998 and 2005, mostly in regions with tree cover less than 70% such as in tropical savannahs of South America and Africa and grasslands across the Asian steppe (Andela et al., 2017). The upper table in Figure 1.5 shows the characteristics of the Global Fire Emissions Database (GFED) fire regions between 2003 and 2016, which identified 13 250 145 individual fires with an average area of 4.4 km^2. On average by region, Australia and New Zealand (AUST) had the largest fires (17.9 km^2), the highest expansion rate (1.7 km^2 d^{-1}) and the fastest speed (1.2 km d^{-1}). On the other hand, fires in Equatorial Asia (EQAS) had the longest duration (5.5 days) (Andela et al., 2019).

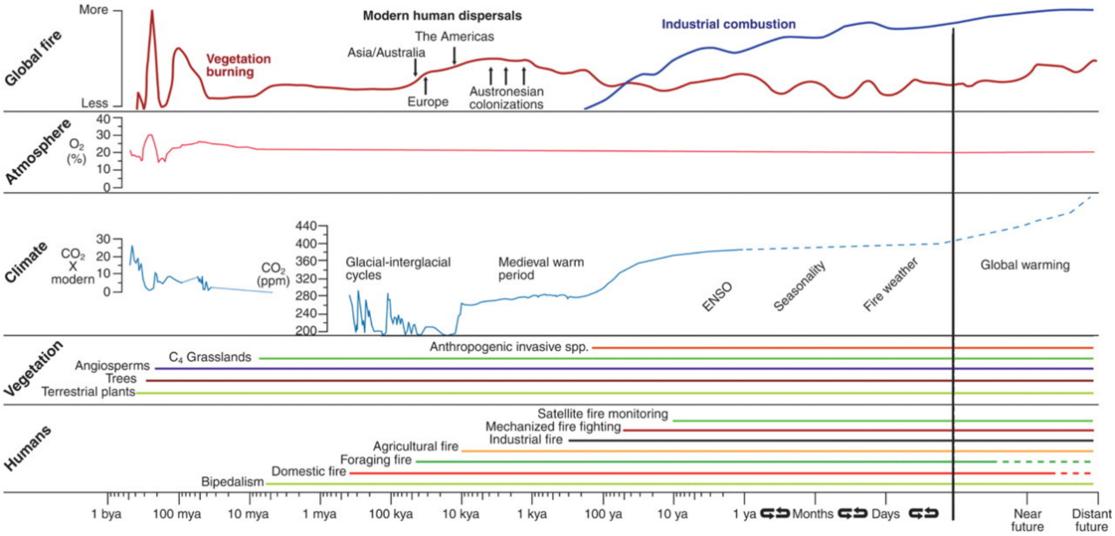


Figure 1.3 Qualitative schematic of global fire activity through time (Bowman et al., 2009).

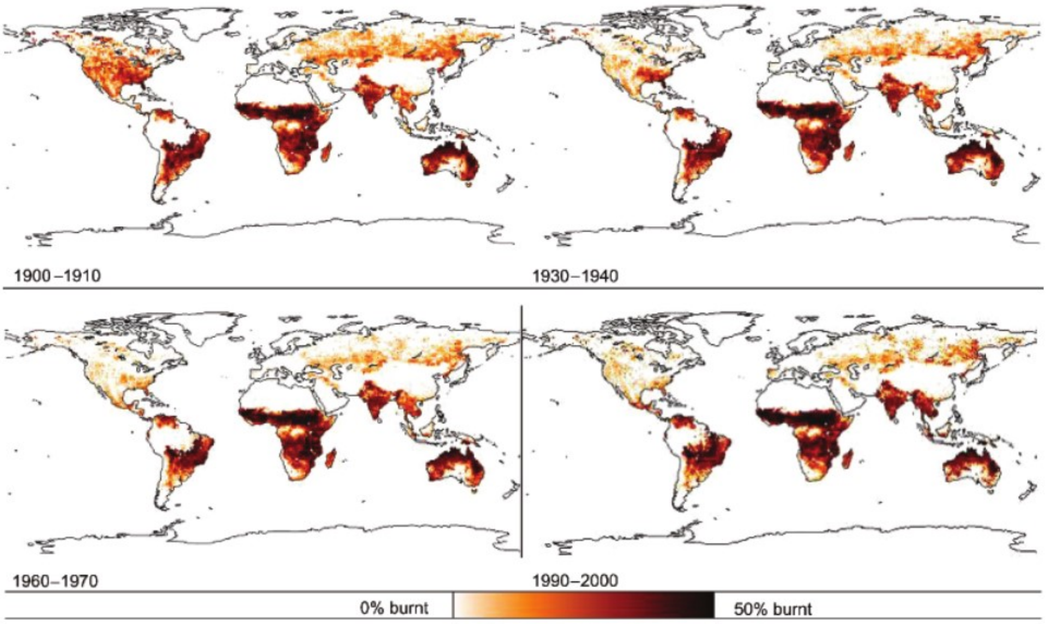
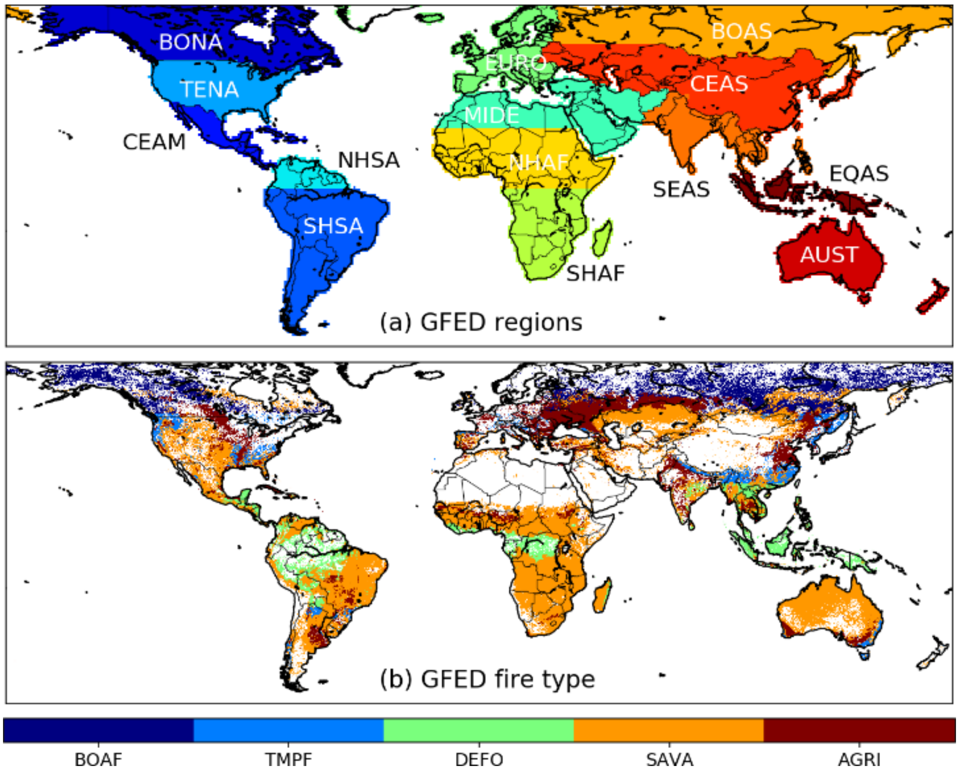


Figure 1.4 Maps of burned area for 1900-1910, 1930-1940, 1960-1970 and 1990-2000 periods in 1° x 1° spatial resolution. Color refers to percentage of cell burned (Mouillot and Field, 2005).



GFED region	Ignitions (2003–2016)	Size (km^2)	Duration (d)	Expansion (km^2 d^{-1})	Speed (km d^{-1})
World	13 250 145	4.4 (395.9)	4.5 (14.7)	0.6 (14.5)	0.9 (3.2)
Boreal North America **(BONA)**	*57 613*	**6.0 (202.8)**	**5.4 (23.3)**	*0.5 (6.8)*	**1.0 (4.3)**
Temperate North America **(TENA)**	*137 900*	*2.9 (136.7)*	**4.7 (13.4)**	*0.5 (8.8)*	*0.8 (3.7)*
Central America **(CEAM)**	*229 245*	*1.7 (28.3)*	*4.3 (12.2)*	*0.3 (1.5)*	*0.7 (1.4)*
Northern Hemisphere South America **(NHSA)**	*242 359*	*3.1 (50.1)*	**5.1 (12.4)**	*0.5 (3.3)*	*0.8 (2.1)*
Southern Hemisphere South America **(SHSA)**	**1 320 177**	*3.0 (90.6)*	**4.7 (13.8)**	*0.5 (4.8)*	*0.7 (2.3)*
Europe **(EURO)**	*71 233*	*2.0 (30.7)*	**4.6 (10.3)**	*0.4 (2.7)*	*0.7 (2.0)*
Middle East **(MIDE)**	*86 783*	*2.3 (22.0)*	*4.0 (9.8)*	*0.5 (2.1)*	*0.8 (1.9)*
Northern Hemisphere Africa **(NHAF)**	**3 517 808**	**5.1 (186.2)**	*4.4 (14.7)*	**0.7 (8.6)**	**0.9 (3.0)**
Southern Hemisphere Africa **(SHAF)**	**5 000 436**	*4.3 (232.5)*	**4.5 (13.5)**	**0.7 (9.6)**	**0.9 (2.6)**
Boreal Asia **(BOAS)**	*363 279*	*3.7 (116.8)*	**4.5 (15.6)**	*0.5 (6.8)*	**1.0 (4.1)**
Central Asia **(CEAS)**	*807 739*	*3.2 (339.7)*	*4.2 (11.5)*	*0.5 (22.7)*	*0.8 (5.6)*
Southeast Asia **(SEAS)**	*937 810*	*2.2 (27.8)*	*4.1 (13.2)*	*0.4 (1.8)*	*0.7 (1.8)*
Equatorial Asia **(EQAS)**	*117 870*	*1.8 (13.5)*	**5.5 (16.4)**	*0.3 (0.8)*	*0.7 (1.3)*
Australia and New Zealand **(AUST)**	*358 807*	**17.9 (2030.6)**	**5.0 (20.5)**	**1.7 (59.5)**	**1.2 (6.1)**

GFED fire type	Ignitions (2003–2016)	Size (km^2)	Duration (d)	Expansion (km^2 d^{-1})	Speed (km d^{-1})
All	13 250 145	4.4 (395.9)	4.5 (14.7)	0.6 (14.5)	0.9 (3.2)
Boreal forest **(BOAF)**	*197 124*	**5.2 (149.2)**	**5.4 (20.1)**	**0.6 (6.5)**	**1.0 (4.2)**
Temporal forest **(TMPF)**	*178 909*	*2.5 (84.1)*	*4.1 (14.0)*	*0.4 (4.2)*	*0.8 (2.8)*
Deforestation **(DEFO)**	*909 826*	*1.4 (28.7)*	*3.8 (13.7)*	*0.3 (1.4)*	*0.6 (1.4)*
Savanna **(SAVA)**	**9 809 719**	**5.1 (447.5)**	**4.6 (14.9)**	**0.7 (16.2)**	**0.9 (3.4)**
Agriculture **(AGRI)**	**1 631 918**	*1.4 (26.4)*	*3.4 (10.3)*	*0.3 (2.0)*	*0.7 (1.9)*

Figure 1.5 Global Fire Emissions Database (GFED) regions and dominant GFED fire types (modified from Andela et al., 2019). Ignitions are the summed ignitions over the study period (2003-2016). Size, duration, expansion and speed are shown as the mean values for individual fires. Also the mean weighted by fire size is provided in parentheses. Over a million ignitions are shown in bold font. For other aspects, values equal to or above the global average are shown in bold font.

1.2 Tropical forests and tropical peatlands

1.2.1 Tropical forests and peatlands

There are a range of definitions and types of forests (Figure 1.6). The United Nations Environment Programme (UNEP) defines forest as “land area of more than 0.5 ha, with a tree canopy cover of more than 10%, which is not primarily under agriculture or other specific non-forest land use. In the case of young forest or regions where tree growth is climatically suppressed, the trees should be capable of reaching a height of 5 m in situ, and of meeting the canopy cover requirement” (Schoene et al., 2007). Remote sensing studies have used other definitions of forests, such as 25% or greater canopy closure at the Landsat pixel scale (30 m × 30 m spatial resolution) for trees >5 m in height (Hansen et al., 2010).

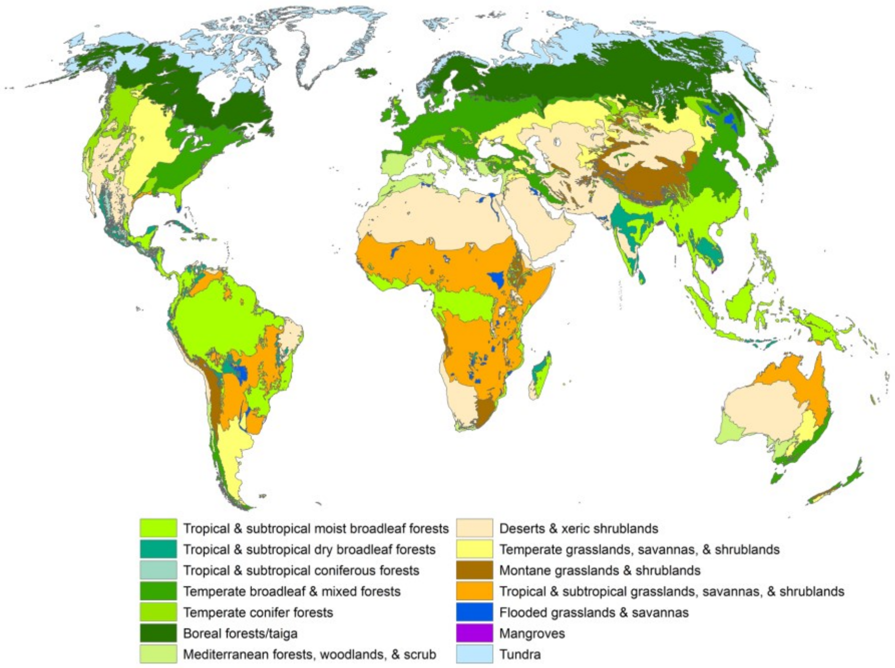


Figure 1.6 World map of coverage of 14 terresterial biomes (Trimble and van Aarde, 2012) adapted from (Olson et al., 2001).

Broadleaf evergreen forests cover 11 Mkm^2 or 7.74% of global land surface (Hansen et al., 2000) spead across the tropics including the Amazon region in South-America, Congo river basin in Africa, and Indonesia-Malaysia area in South-East Asia. Those forest areas store 193 Gt of carbon (C) aboveground and 54 Gt C belowground in roots, distributed 49% in Latin America, 25% in sub-Saharan Africa and 26% in Southeast Asia (Saatchi et al., 2011).

Its important to highlight that some fraction of tropical forests are located on peatland (

Figure 1.7). Peatlands cover over 4 million km^2 or 3% of the Earth surface, distributed in North America (1 415k km^2), Asia (1 070k km^2), Europe (617k km^2), South America (25k km^2) and Africa (10k km^2) (Joosten and Clarke, 2002). In Southeast Asia, peatland covers 83k km^2 Mha in Sumatra Island, 68k km^2 in Kalimantan provinces (Indonesia's part of Borneo Island) and 46k km^2 in Irian provinces (Indonesia's part of Papua Island). The exact extent of peatland is challenging to measure mainly due to differences in definition. For example, some definitions specify peatland with 30 cm minimum thickness of material containing at least 30% organic matter while in others peat soils are defined as soils having more than 65% organic matter with at least 50 cm thickness (Page et al., 2007).Its estimated that peatland in Indonesia is between 149k and 271k km^2 which mainly located in Sumatra, Kalimantan and Papua islands (Wahyunto et al., 2016). Figure 1.8 shows the distribution of peatlands in Indonesia.

Peatlands produce ecological, climate and socio-economic benefits both locally and globally (Harrison et al., 2019). The long-term support of lowland tropical peatlands for indigenous people with food, shelter, medicine and cultural well-being may continue if the ecosystem characteristics are understood and sustainably managed but recently have been threatened by logging, drainage and expansion of agricultural areas (Page et al., 2006). Tropical peat usually is a result of tree decomposition in wet conditions (Figure 1.9), therefore they store more carbon than moss derived peatland as they cover ~11% of global peatland area and have 81.7-91.9 Gt or 15-19% of the global carbon pool with 57.4Gt located in Indonesia (Page et al., 2011).

The physical and chemical characteristics of the peat materials mean they can be considered as plant's growth medium as well as an energy source (Andriesse, 1988). Peat's enormous capacity for absorbing water keeps the lower part wet even when the upper soil is dry, but when the surface peat soil dries it easily burns resulting in a white smoke-water vapour mix (Adinugroho et al., 2005).

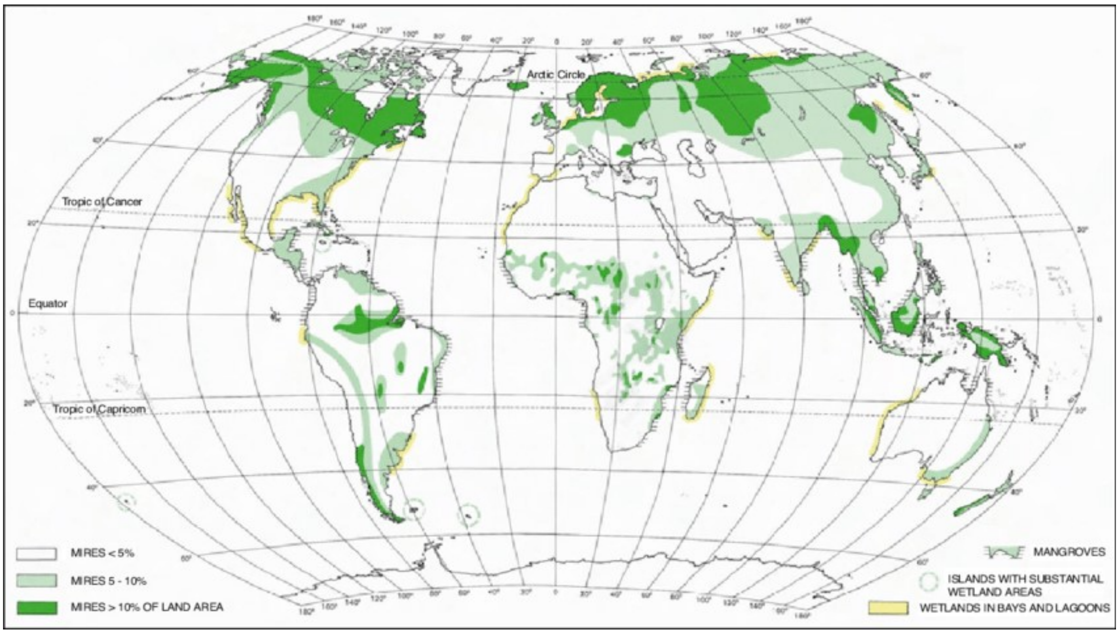
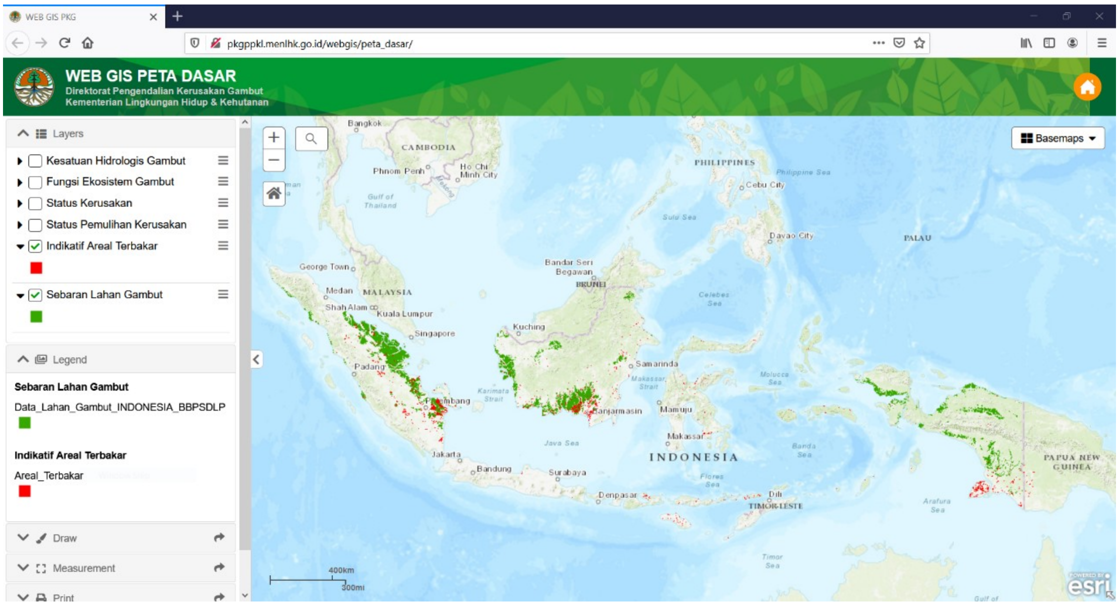


Figure 1.7 Global Peatland Map (Lappalainen, 1996).



Layers

- ☐ Kesatuan Hidrologis Gambut
- ☐ Fungsi Ekosistem Gambut
- ☐ Status Kerusakan
- ☐ Status Pemulihan Kerusakan
- ☑ Indikatif Areal Terbakar 🟥
- ☑ Sebaran Lahan Gambut 🟩

Legend

Sebaran Lahan Gambut

Data_Lahan_Gambut_INDONESIA_BBPSDLP 🟩

Indikatif Areal Terbakar

Areal_Terbakar 🟥

Figure 1.8 Distribution of Peatland in Indonesia (green) and burnt area (red). Source : http://pkgppkl.menlhk.go.id/webgis/peta_dasar/. Accessed 14 November 2020.

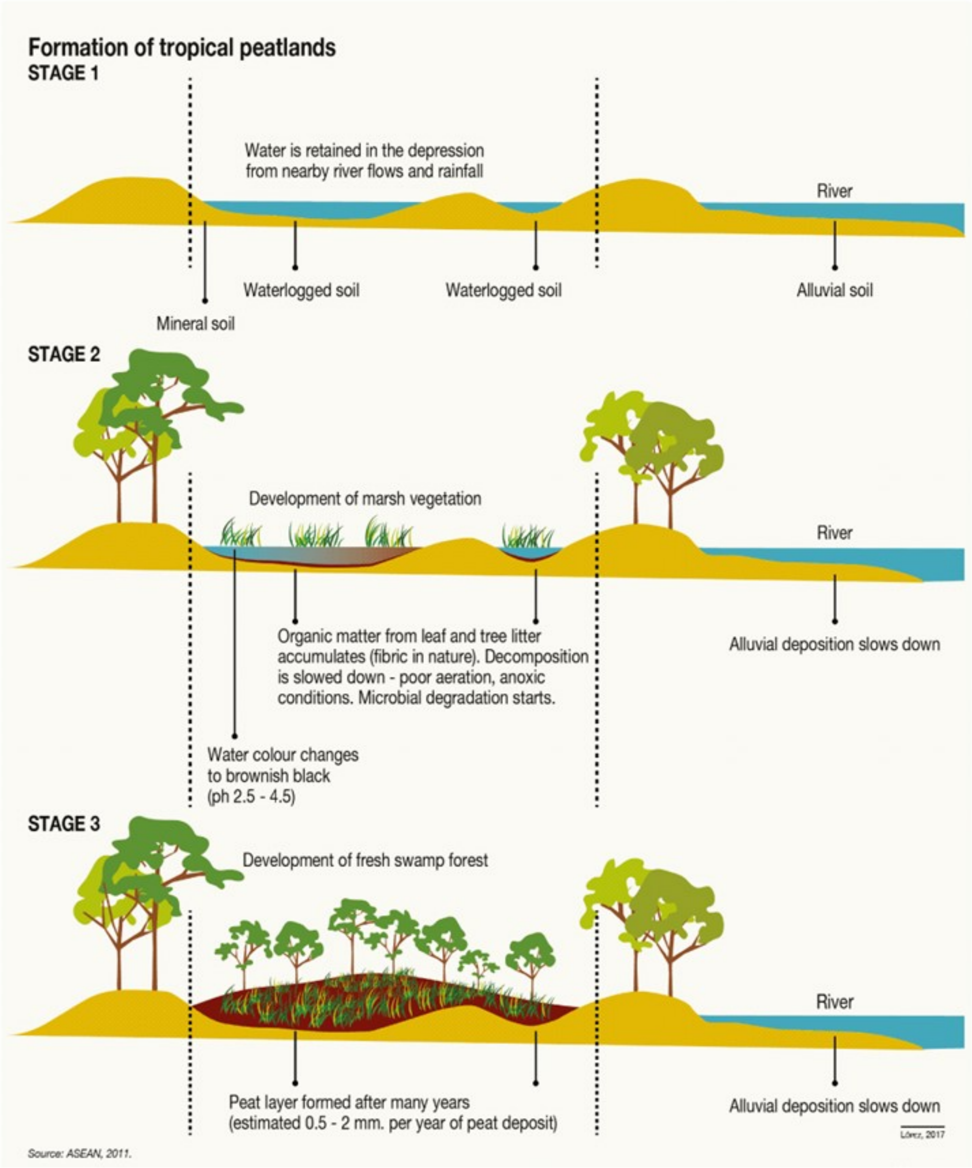


Figure 1.9 Formation of Tropical Peatlands (Izquierdo, 2017).

1.2.2 Land-use change

Land use refers to, "man's activities on land which are directly related to the land" (Clawson and Stewart, 1965). Land cover, on the other hand, describes, "the vegetational and artificial constructions covering the land surface" (Burley, 1961). Land use and land cover change (LULCC) is the human-caused changes that affect the biophysics, biogeochemistry, and biogeography of the terresterial surface (Pielke et al., 2011). Another definition is land cover or land use change indicates the changes occurring to the land cover or land use over time. These may be natural successional changes, natural events or due to climate change or human intervention (GSARS.org, 2016).

Conceptually, there are links between land change, actors and driving forces (Hersperger et al., 2010). Actors can be individuals, agencies and institutions which make decisions, act accordingly, and influence other actors and the environment with their actions, for example farmers and investors who directly change lands or political parties and administrative entities which affect policies and markets (Hersperger et al., 2010). Driving forces form a complex system of dependencies, interactions and feedback loops and they affect several temporal and spatial levels (Bürgi et al., 2004). Major driving forces are social-economic, political, technological (e.g. techniques, education skill, cooperation and management), cultural (e.g. tradition and ideology) and natural (e.g. geomorphology, soil, climate and hydrology) (Brandt et al., 1999).

Predominant land-use change varies by region, including tropical deforestation and agricultural expansion, temperate reforestation or afforestation, cropland intensification and urbanization (Song et al., 2018). Deforestation is projected to cause major global impacts because it changes rainfall patterns and surface temperatures (Greenpeace, 2013). WWF (2015) defines deforestation fronts are the places where the largest concentrations of forest loss or severe degradation are projected between 2010 and 2030. The report also describes three types of deforestation front, namely a hard front with a distinct edge in intact forest, a dispersed front with numerous loss patches and a scattered forest front with progressive loss in a forest-grassland ecosystem. The list of the deforestation fronts and projections of likely losses (in million hectare) are : Amazon (23-48), Atlantic Forest/Gran Chaco (10), Borneo (22), Cerrado (15), Chocó-Darién (3), Congo Basin (12), East Africa (12), Eastern Australia (3-6), Greater Mekong (15-30), New Guinea (7) and Sumatra (5). Keenan et al. (2015) reported that tropical forest area declined at a rate of 5.5 Mha year^{-1} during 2010 – 2015.

As natural driving force, a changing climate can lead to changes in land use and land cover. For example, farmers might shift from their customary crops to crops that will have higher economic return under changing climatic conditions (Msofe et al., 2019). Also, land use change is an important driver of climate change. For an instance, due to forest loss tropical forest are likely to become a carbon source (Mitchard, 2018). Naturally, tropical forests make an approximately neutral contribution to the global carbon cycle since capturing around 72 Pg C from the atmosphere ever year trough photosynthesis and release a similar amount back through respiration of trees and other living things (Mitchard, 2018).

Figure 1.10 shows the dynamics of decreasing or increasing carbon deposits is strongly influenced by land use activities, therefore the most important part in forest management is to set a forest definition that can be used as a guideline in the technical level (Nurrochmat et al., 2016).

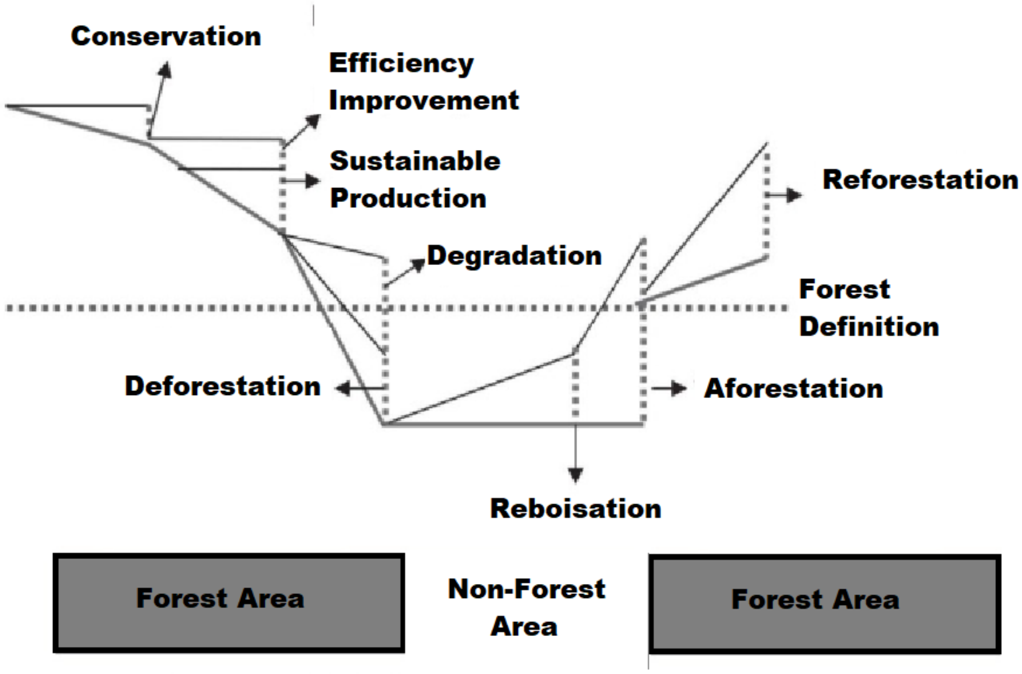


Figure 1.10 The dynamics of carbon stocks in various land use activities (modified from :Nurrochmat and Abdullah, 2014).

In Sumatra island where Riau Province is located, the primary cause of forest loss and/or severe degradation are small-scale agriculture & colonization and infrastructure. Meanwhile, unsustainable logging, pulp plantations and fires are the important secondary cause. In addition, large-scale agriculture plays a less important role (WWF, 2015). In addition, Rijal et al. (2016) shows that from 152 regencies/cities in Sumatra Islands, 31% were experiencing deforestation in areas with low forest cover and occurred in the first period with a high rate in the initial period.

1.2.3 Land-use change Relationships between land-cover change and fire

Figure 1.11 shows the interrelationships between tropical land-cover change and forest fire which involve phenomena such as deforestation, forest fragmentation, logging and road building. Cochrane (2003) describes events in that interrelationship as:

a. “Logging results in limited amounts of deforestation for roads and log landings. Post-logging colonization can increase deforestation”
b. “Logging degrades forest, increasing fire susceptibility”
c. “Deforestation fragments the remaining forests, increasing amounts of forest edge”
d. “Forest edges suffer biomass collapse and microclimate changes making them susceptible to frequent fires”
e. “Repeated forest fires can lead to unintentional deforestation”
f. “Deforestation and pasture/land maintenance fires result in many accidental forest fires”
g. “Forest fires can create a positive feedback cycle where recurrent fires become more likely and more severe with each occurrence”

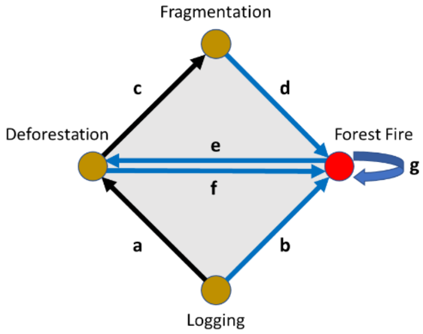


Figure 1.11 Diagram of interrelationships between tropical land-cover change and forest fire. Blue arrows : direct force, black arrow : undirect force, letter labels : event (details in text) (modified from : Cochrane, 2003).

Furthermore in the case of Southeast Asia, Murdiyarso and Lebel (2007c) emphasize several human controlled aspects in the case of fire regime change. Figure 1.12 shows that fire regimes are affected by ecoystem condition, land management practices and climate. Agriculture and forest management practices depend on land development incentives including (1) land tenure regime, i.e. local and state property rights to land and land-derived resources, and (2) various sets of policies which strongly impact on land development.

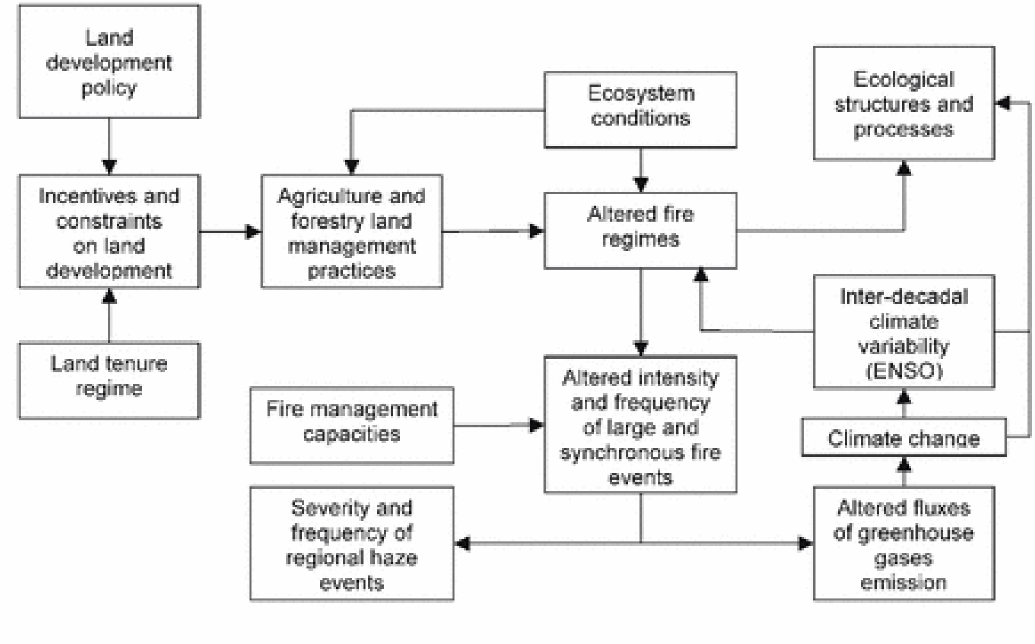


Figure 1.12 Conceptual Framework of Fire Regime Alteration in Southeast Asia (Murdiyarso and Lebel, 2007b).

In consequence of climate variations, vegetation types, human activities and intensity, land fire regimes across Southeast Asia are different among different locations. In 1998-2001, while regions of woody grassland burnt very frequently, moist tropical forests were very rarely burned (van der Werf et al., 2003). Later (2000-2006), fire in Borneo and Sumatra increased due to drought and also deforestation (van der Werf et al., 2008).

1.2.4 Fire in tropical forests

Figure 1.13 points out the relationship between fires and phases of vegetation succession in peat swamp forest. Undisturbed tropical peat swamp forests have a water table that is constantly close to the surface. Long and wide drainage canals became a common part of plantation development on peatland since oil palm and Acacia grow best when water levels are more than 50 cm below the peat surface, and canals can also be used to transport logs (Page et al., 2009). The drop of water level increases aerobic degradation and resulting large amount of fuel from dry peat. In addition, logging opens up the forest canopy which boost fire prone vegetation on the forest understory. Later, the degraded forest may regenerate if experiencing no fire (progressive succession) but probably turn into heavily degraded forest or non-forest vegetation after having repeated and high-intensity fire events then finally ended as savannah (Page et al., 2008; Page et al., 2013)

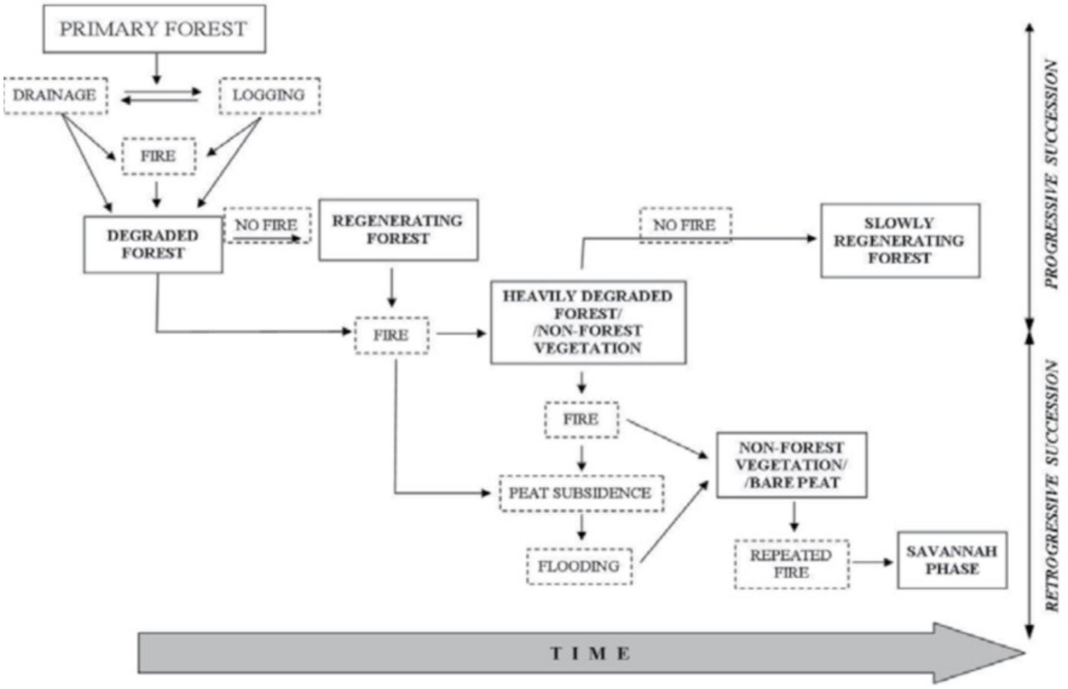


Figure 1.13 Relationship between single and multiple fires and phases of vegetation succession against time in peat swamp forest (Page et al., 2013).

1.3 Fire in Indonesia

Forest and peatland fires occur annually across Indonesia, resulting in large greenhouse gas emissions, causing major regional air quality issues, related to economic loss and damaging other environmental aspects. Some details of those issues are:

a. Emissions from vegetation and peat fires in Indonesia in 1997 was estimated to be equivalent to 13-40% of the mean annual global carbon emissions from fossil fuels (Page et al., 2002). The large fires across Indonesia in September–October 2015, emitted 700–800 Tg CO_2 (Huijnen et al., 2016; Kiely et al., 2019). The massive carbon emission contribute to global warming and potentially influence the El Niño-Southern Oscillation (ENSO) which will increase future fires (Harrison et al., 2009).
b. Fire also cause severe regional air quality issues (Crippa et al., 2016; Marlier et al., 2013), especially peat fires because they emit large amounts of fine particulate matter (PM2.5) and up to ~90 gases (Jayarathne et al., 2018; Stockwell et al., 2016). Approximately, 69 million people in Indonesia were exposed to poor air quality during the severe fire season in 2015 (Crippa et al.,

2016). Exposure to particulate pollution in 2015 is estimated to have caused 11,880 mortalities in the short term (Crippa et al., 2016) with as many as 100,300 premature mortalities over the longer term (Koplitz et al., 2016). Peatland regions experiencing rapid land cover change and frequent fires in central and southern Sumatra and southwest Kalimantan contribute the most to regional air quality issues (Reddington et al., 2014)

c. Fire may cause economic loss directly due to burning properties or crops and fire suppression expenses. Fire also incurs indirect costs to regions or countries such as through lost workdays, production slowdown and reduction of tourism (Cochrane, 2009). It is estimated that forest fires and haze in June-October 2015 caused USD 16 124 million of losses and damages in Indonesia (TWB, 2016).
d. Some others environmental aspects also suffer negative impacts of fire. For example, Kinnaird and O'Brien (1998) reported the increment of post-fire tree mortality and substantial reptile mortality in fire-impacted areas in southwest Sumatra. In addition, species richness in peat swamp forests in Kalimantan was significantly reduced just 1-2 months after the fires (Yeager et al., 2003). Since pollinators are killed by fire, subsequent year’s crop production may be reduced (Cochrane, 2009).

The issue of fires in Indonesia are perceived differently by different stakeholders. Table 1.1 explains how the occurrence of fire in Indonesia has received various perspectives from local to global levels (Murdiyarso and Lebel, 2007a).

The occurrence of fire in Indonesia is influenced both by climate (Fanin and van der Werf, 2017; van der Werf et al., 2008) and by extensive land-cover change (Langner et al., 2007). Extensive fires in Indonesia mainly occur during dry years linked to the El Niño Southern Oscillation and the Indian Ocean Dipole (IOD) (Fanin and van der Werf, 2017), with a nonlinear sensitivity of fire to dry conditions (Field et al., 2016). However, despite the occurrence of drought years, large fire events did not occur prior to the 1960s in Sumatra and the 1980s in Kalimantan, periods when extensive land-cover change began (Field et al., 2009). Undisturbed tropical forests and peatlands are typically sufficiently wet to be resistant to fire (Cochrane and Schulze, 1999; Page et al., 2002).

Table 1.1 Perspectives on fires at different geographic levels (Murdiyarso and Lebel, 2007a).

Level	Negative perspectives	Neutral or positive perspectives
Local	Fires damage property and degrades forests	Fire is a convenient tool to convert and prepare land for agricultural activities
National	Fires are a national embarrassment and diplomatic challenge. International media portrays country as unable to manage own environment properly	Fires are a tool and smoke is a necessary by-product of land and economic development
Regional (Southeast Asia)	Fires cause deforestation and biodiversity loss. Smoke costs tourism and transport income	Fires are a tool and smoke is a necessary by-product of investments in plantations
Global	Fires contribute to climate change through large fluxes of greenhouse gas emissions and reducing carbon stocks	Fire are an inevitable and partly natural (cyclic) phenomena in terrestrial ecosystems. They renew and destroy

However, over the last few decades, Indonesia has also experienced extensive forest loss and conversion of forest to oil palm and wood fiber plantations (Gaveau et al., 2016; Harris et al., 2017). Between 1973 and 2015, 14.4 Mha of primary natural forest in Borneo was cleared (Cochrane and Schulze, 1999). The rate of tree cover loss in Indonesia increased from less than 10 000 km^2 yr^{-1} in 2000–2003 to over 20 000 km^2 yr^{-1} in 2011–2012, resulting in one of the largest increments of tree cover loss rate worldwide (Hansen et al., 2013), although forest loss rates include clearance of timber plantations and oil palm estates. In total, 60 200 km^2 of primary natural forest loss occurred across Indonesia over the period 2000 to 2012, increasing by 476 km^2 yr^{-1} (Margono et al., 2014). The largest increase of primary tree cover loss occurred in wetland (peat) areas and almost all clearing of forests occurred on previously degraded land, meaning logging preceded land conversion. Forests in Indonesia contain important aboveground and below ground carbon stocks (Ekadinata and Dewi, 2011; Harja et al., 2011), meaning forest loss will alter the carbon balance in the region. Indonesia’s largest single driver of deforestation in 2001–2016 was oil palm plantations, which contributed 23% of deforestation nation-wide (Austin et al., 2019). Recently, the dominant role of logging in the transformation of peat swamp forests in Southeast Asia has also been emphasized (Dohong et al., 2017).

Land-cover change is connected to fire through a multi-year process involving road building, logging, and forest fragmentation (Cochrane, 2003; Juárez-Orozco et al., 2017). Also, deforestation and forest degradation provide abundant fuels, and drainage of peatland soils accelerates groundwater drawdown increasing the flammability of peat (Taufik et al., 2017). Fires now occur annually across extensive regions of Indonesia, even in years without drought (Gaveau et al., 2014). Putra et al. (2019) demonstrate that more than 80% fires occur in area with less than 20 cm groundwater level. On average the peatlands in Kalimantan and Sumatra have 28 and 45 years of recurrent burning, respectively (Vetrita and Cochrane, 2020). This demonstrates how anthropogenic land-cover change has modified the occurrence of fire across Indonesia.

One of the regions with the highest fire frequency is Riau Province. Fire started in Riau Province in the early 1960s as agro-industry and agricultural activities increased (Bowen et al., 2001). In Riau province, more than 90% of the area of severely burnt primary vegetation eventually changed land cover type over the period 1998–2002 (Miettinen and Liew, 2005). In that province, fire was used as a tool for land preparation by oil palm companies, industrial timber plantation, and smallholders, with crop planting often occurring shortly after burning, suggesting a link between fire and land-use change (Suyanto et al., 2004). Albar (2015) found that 72% of fire hotspots in Riau Province during 2006 to 2013 occurred within non-forest areas, with the number of fire hotspots increasing over this period burning affected peatland area in Sumatra (mostly in Riau and South Sumatra Province) at rates five times higher than non-peatlands (Vetrita and Cochrane, 2020).

1.4 Causes of Fires in Indonesia

Forest fires are closely related to land cover dynamics in Indonesia. Fire activity is mostly detected in wood fiber (timber) concessions, both in Sumatra (Marlier et al., 2015) and Kalimantan (Langner and Siegert, 2009). Burn risk seems related to high fuel stored in the vegetation due to poor maintenance (Saharjo, 1997). In Sumatra, 58% of the fires in 2013 occurred on land that had been forest five years previously (Gaveau et al., 2014). In Kalimantan, enhanced fire frequency occurs within 10 km of oil palm, with oil palm extent associated with increased fire frequency until covering 20% of an area (Sloan et al., 2017). Comparing land-use and land-cover between one year before and three years after fire occurrences in Jambi, shows that 20% of the area burned by fires became forest plantation, 27% became oil plantation and 52% was converted into small holder/community land area (Prasetyo et al., 2016).

There are four major direct causes of fires in Indonesia: fire used as a tool in land clearance; accidental or escaped fires; fire used as a weapon in land tenure or land-use disputes; and fire connected with resource extraction (Applegate et al., 2001; Dennis et al., 2005). Applegate et al. (2001) identified five underlying causes of fire: land tenure and land use allocation conflicts and competition, forest degradation practices, economic incentives/disincentives, population growth and migration, and inadequate firefighting and management capacity. Table 1.2 lists direct and underlying causes of fires in Indonesia and their relative importance. High importance direct causes are fires as a tool in land clearing and accidental fires (escaped), while significant underlying causes are conflicts between stakeholders, lack of a transparent legal systems, profitability of alternative land use and perverse development processes and mechanisms (Applegate et al., 2001)

Vayda (2006) recommends a distinction between an explanation of the start of fires and the way they spread, for example arson, the facilitation of access to resources, and the clearing of land for swiddens and plantation related to ignition events. On the other hand, other causes such as changes in forest microclimate, the build-up of fuel loads, both intensive logging and specific forestry policies pertain to spread of fires.

Table 1.2 Direct and underlying causes of fire in Indonesia (Applegate et al., 2001).

CAUSES	IMPORTANCE
DIRECT CAUSES	
Fire as a tool in land clearing	HIGH
• Small holders	High
• Large holders (companies/government)	High
Fire as weapon in land tenure	MODERATE
Accidental fire (escaped)	HIGH
Fire connected with resource extraction	LOW
UNDERLYING CAUSES	
Land use allocation	HIGH
• Inappropriate and/or uncoordinated land use allocation	High
Land tenure	VERY HIGH
• Informal land tenure security promotes site occupation and forest conversion	Low
• Increase “private” land rights with tree planting on communal forest and land according to customary low	Low
• No inventive for local communites to control unwanted fires	High
• Conflicts between stakeholders including local communities, migrants, large companies and forest managers	Very High
• Lack of a transparent legal system to address land claims and traditional communal rights	Very High
Shift in demographic characteristics	MODERATE
• Large scale in migration	High
• Lack of commitments to new location and careless use of fire	Low
• Inexperience with use of fire in new environments	Low
• Different resource use patterns (fire) by different etnic groups	Low
Forest degrading practices	MODERATE

CAUSES	IMPORTANCE
• Inappropriate timber harvesting system and practices	High
• Drainage systems in swamps that lower the water table, dries the forest and provide increases access	Low
• Repeated fires due to increased fire proneness of previously burned vegetation	Moderate/High
Economic incentives/disincentives	VERY HIGH
• Profitability of alternative land use (e.g. coffee, small holder rubber)	Moderate
• Profitability of alternative land use (e.g. oil palm, rubber, timber)	High
• Perverse development processes and mechanisms	Very High
Inadequate institutional capacity	LOW
• Lack of institutional capacity, resoures and will to monitor and deal with encroachment and other illegal activities in forest areas	Low
• Inadequate forest and fire management plans, and facilities to prevent and suppress accidental or escaped fres in plantations and natural forest	Low

1.5 Fire in Peatland

Peat fire can be divided into surface peat fire and deep peat fire. Figure 1.14 illustrates how fire develops in tropical peatland through the following steps (Usup et al., 2004) :

1. Stage I : a spot of fire is ignited during the surface fire event which burns surface fuels. This fire goes though cracks or woody materials, or assemblages of litter in small cavities reaching the peat soil.
2. Stage II : after surface peat had been ignited, a smoldering front starts to burn laterally and downward, burning grass roots, humus and small woods fragments at a depth of 0-20 cm with 3.83 cm hour^{-1} average speed.
3. Stage III : deep peat fire burns at >20 cm depth with the main fuel being large woody fragments and peat matrix. The high wood content and low bulk density of the deeper peat layer enables oxygen to be

supplied. When smoldering combustion occurs here it moves with 1.29 cm $hour^{-1}$ average speed.

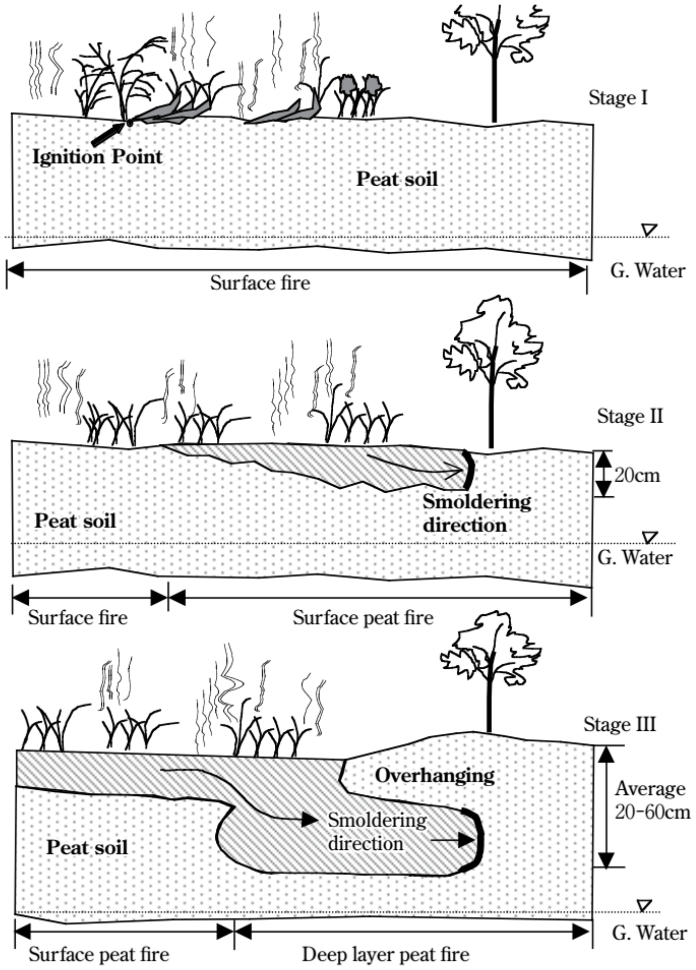


Figure 1.14 Diagram of Peat Fire Development (Usup et al., 2004).

1.6 Methods Used for Detecting Fire Occurrence

Evenly arranged and consistent measurements over time and space from satellite data are important in fire disturbance monitoring and reporting (Hislop et al., 2020). Hardy (2005) mentioned “fire risk” as the probability of ignition by both human and natural causes. In addition, “fire hazard” refers to the state of the fuel, independent of weather including aspects such as fuel arrangement, fuel load, condition of herbaceous vegetation, and presence of elevated fuels. The report also cites “fire severity” as the magnitude of significant negative impacts on wildland systems (Simard, 1991).

Fire produces four phenomena which can be sensed remotely such as the radiation of heat and light, smoke, char and fire scars (Martín et al., 1999; Robinson, 1991a). Its estimated that 10–20 % of the heat is emitted from the combustion zone as electromagnetic radiation of various wavelengths (Byram, 1959). The thermal radiation of ongoing smouldering and flaming are called “active fires” (Kaufman et al., 1998). Remote sensing of active fires has spatial, temporal and thermal sensitivity issues (Martín et al., 1999). Spatial issues occur because active fires could occupy only a very small proportion of a pixel because the highest ratio between hotspot irradiance and background irradiance happen in the middle infrared (MIR) wavelengths (Robinson, 1991a). Therefore, one or more active fires may reside in a single pixel, or an active fire may only occupy a portion of a larger fire front (Martín et al., 1999). Temporal limitations arise because many active fire are missed due to their short life time (Prins, 2001). The MODIS platform produces active fire products within 4 to 6 hours from acquisition time, after passing through an atmospheric and reflectance correction (Sohlberg et al., 2001). The last problem is thermal sensitivity since cloud is a significant error source for fire discrimination using MIR channel (Chuvieco and Martín, 1994). Later, the MODland algorithms for MODIS sets the saturation temperature of the 11 μm band to avoid saturation over flaming so fit for active fire monitoring (Justice et al., 2002b). Radiation from flaming combustion can be highlighted using a true colour composite of visible wavelengths, while a false colour composite of shortwave infrared wavebands makes actively burning and already burned areas prominent due to its ability to penetrate the smoke (Amici et al., 2011).

Although the location and timing of fires burning can be provided by active fire products, they do not always allow reliable burned area estimation (Giglio et al., 2009). Scholes et al. (1996) reports that, in southern Africa, burnt area was underestimated in arid regions due to a few large fires but overestimated in moist regions because a high number of small fires. In tropical regions of Central Africa, Eva and Lambin (1998) found biomass burning affected by temporal sampling of active fires, thus decreasing the statistical representative of the observations. A study in the boreal forest area of Alaska and Canada suggests that the number of potential fire pixels should be lower for an individual fire event during the larger fire years because the length of the active fire perimeter determines satellite detection of fires (Kasischke et al., 2003). Global estimation of burned area using mean percent tree cover, percent herbaceous vegetation cover and percent bare ground as inputs for regional regression trees discovered that neither a constant or adjusted effective area per fire pixel are satisfactory (Giglio et al., 2006)

Another approach to detect burned areas is by observing deposits of charcoal and ash, calculating reduction in the amount of vegetation, and detecting vegetation structure change (Pereira et al., 1997; Roy et al., 1999). However, ash may be redistributed or removed from a burned site within days or weeks by wind and water erosion (Bodí et al., 2014). On the other hand, a fire-charred surface absorbs almost all electromagnetic spectrum so it does not allow for sub-pixel burn evaluation, thus the minimum size of the target area is 3 pixels (Robinson, 1991b). Compared to the previously mentioned approach, the alteration of vegetation structure and abundance is more stable, although its persistence may vary from 2-3 weeks in tropical grasslands to several years in boreal forest ecosystems (Pereira et al., 1997). The areas that are destroyed by forest fire which are not yet recovered, namely burn/fire scar, is the most commonly used evidence of past fire (Johnson and Gutsell, 1994; Liu et al., 2014). Although burn scar detection is reliable, they can be confused with scars resulting from other causes such as mechanical (i.e. logging activities, road construction, and windthrow), biological (i.e. pathogen and insect) or environmental (i.e. frost and lightning) (Johnson and Gutsell, 1994; Molnar and Mcminn, 1960).

Pereira (1999) compared the capacity of several vegetation indices (VIs) to discriminate between burned and unburned surfaces using single date images. He found that the normalized difference vegetation index (NDVI) and VI3 has a considerable error in labelling drier surfaces as burnt areas, and the global environmental monitoring index (GEMI) has some degree of confusion between the dark burns and land cover types, such as wetlands and water bodies. Furthermore, Roy et al. (1999) introduced a burn scar index change map (the maximum minus the minimum burn scar index value over a given period) which is able to incorporate biophysical and empirical based thresholds. Later, Chuvieco et al. (2006) built the composite burn index (CBI) as burn severity indicator from the change in soil and charcoal spectra, percentage of foliage altered (PFA) and percentage change in leaf cover (PCC, derived from leaf area index - LAI). Furthermore, they measure the reflectance of individual wave bands in the 400–2500 nm range, and finally use a radiative transfer model (RTM) to inverse CBI from the combination of NIR and shortwave infrared reflectance. Determination coefficients of this model range between 0.436 (MODIS) to 0.629 (Landsat-

TM) while the intermediate range of CBI values have lower precision (Chuvieco et al., 2007). A broader assessment of Normalized Burn Ratio (NBR), delta Normalized Burn Ratio (dNBR), and NDVI indices on Landsat 5, SPOT 4, ASTER, MASTER and MODIS imagery shows that vegetation variables produced a higher proportion of meaningful correlations than ground and soil attributes (Hudak et al., 2004). In summary, though the instruments on satellites are troublesome to sense surface fires under dense tree cover (Pereira et al., 2004), the differences in spectral or thermal properties of a land surface between pre- and post-fire events are applicable to delineate burned area (Lentile et al., 2006). It should be noted that multi-temporal approaches faced challenges from radiometric and geometric adjustments, as well as confusion due to temporal change such as seasonal floods, harvesting or deforestation (Chuvieco et al., 2019).

1.7 Review of Previous Research on Relationships Between Forest Fire, Land Use and Land Cover in Tropical Rain Forest

Some studies suggest that fire is directly connected to land cover change since degraded forest increases fire susceptibility, biomass collapse and microclimate change in forest edges are prone to frequent fires, and land maintenance fires may cause accidental wildfire (Cochrane, 2003). The direct interaction between fire and deforestation is also related to land condition (Lavorel et al., 2006). Dennis et al. (2005) explains four major direct factors of fires in Indonesia: fire used as a tool in land clearing; accidental or escaped fires; fire used as a weapon in land tenure or land-use disputes; and fire connected with resource extraction. Also, five underlying causes are identified : Land tenure and land use allocation conflicts and competition, forest degrading practices, economic incentives/disincentives, population growth and migration, inadequate fire fighting and management capacity. Marlier et al. (2015) also found that 2003-2013 fire activity was mostly detected in timber concessions (Sumatera) and oil palm concessions (Kalimantan), while the lowest occurrences in both islands observed in logging concessions. In addition, by comparing land use and land cover between one year before and three year after fire occurrences in Jambi Province, Sumatra, Prasetyo et al. (2016) shows that a fifth of fire incidence was followed by forest plantation, 27% become oil plantation and 52% were converted into small holder/community land area.

A study in the northern part of Riau province shows that almost half of the fire in 1998, 2000 and 2002 occurred on less than 5% of the study area, and were mostly located near established plantations (Miettinen and Liew, 2005). That report also reveals that more than 90% of the severely burnt primary vegetation area eventually changed land cover type over the period. Suyanto et al. (2004) suggested that fire was linked with plantation preparation and housing development in Petatahan District, Riau. They also found that timber or crop planting began less than a month after burning, suggesting a link between fire and land-use change. Later, (Tonoto, 2011) shows that 70% of hotspots in Riau Province in 2010 were found in shrub area which had been encroached by people but not yet converted into palm oil plantation.

Fire usage for land clearing agree with the finding of Albar (2015), who found 72% of fire hotspots in Riau Province during 2006 to 2013 occurred within non-forest areas, with the number of fire hotspots increasing over this period. In addition, shrub areas are the most fire prone land cover type regardless of their land management and ownership. On the other hand, unregistered palm oil plantations had more fire than registered or small holder plantations (Tonoto et al., 2017). Its not uncommon that fire is triggered by land tenure conflicts between plantation companies and local communities (Suyanto et al., 2004). Many actors may be involved and benefit from fire usage in Riau; farmer organizers received 57% of financial benefit of up to $486 per hectare, and they had the capability to determine land management decision making (Purnomo et al., 2017). Those organizers are land claimers, political party members, and community leaders. They organize farmers and local people into farmer groups, then together with village and district officers manage land administration and documentation. The connection between palm oil and local officers was also observed in East Kalimantan Province through power dynamics such as coercive, incentive and information domination among those actors (Prabowo et al., 2017). A study in Central Kalimantan Province shows the different position among bureaucracy elements regarding the legalization of non-procedural forest to oil palm conversion (Setiawan et al., 2016).

Those above mentioned reports emphasize how government policy strongly shapes land and forest management forms. In order to support the government to find land management policy which may bring benefit to the community and at the same time be environmentally sustainable, it is necessary to discover the relationships between fire hotspot, land use and land cover change. Technically, the co-location of fire with respect to land-cover data in the tropics could be found using high resolution remote sensing imagery (Eva and Lambin, 2000). Later, Barbosa et al. (2000) analysed the land cover change after fire in Portugal. Using Atmosphere Resistant Vegetation Index (ARVI) differencing, forest change was identified but no comparison between pre/post fire land cover change was made. Finally, Fanin and van der Werf (2015) evaluated the spatio-temporal dynamics of deforestation (from Hansen's GFC) and fire (represented by MODIS burned area) in the Brazilian Legal Amazon.

1.8 Research Questions and Objectives

There is an urgent need to better understand how agricultural and plantation management can be altered to minimize fire and associated environmental impacts.Therefore, the overall aim of this thesis is to explore the relationships between fire, land cover and land cover change in Riau Province, Indonesia.The research objectives of this thesis are :

1. Analyze the occurrence of fire and tree cover loss, as well as information on the extent of peat land, protected areas, and concessions to explore spatial and temporal relationships among forest, forest loss, and fire frequency in Riau Province, Indonesia.
2. Assess the association of fire with specific land cover types and land cover transitions in Riau Province, Indonesia.
3. Create models of the fire risk in Riau Province, Indonesia using identified relationships between fire hotspots, tree cover loss, land cover type and land cover transitions.

1.9 Thesis Structure

The thesis is divided into six chapters.

This Chapter (Chapter 1) presents an introduction to vegetation and peat fire with a focus on tropical fires. The links between fire hotspot and land use / land cover change are discussed. It includes the sources, roles and conseqences of those disturbances. It also highlights previous research on relationships between forest fire and land use / land cover change in Indonesia.

Chapter 2 provides an explanation of the datasets and methods used in this thesis.

Chapter 3 contains findings related to the first reseach objective, reporting links between fire and tree cover loss (Objective 1).

Chapter 4 reports the association of land cover transition with fire (Objective 2).

Chapter 5 reports fire risk models based on relationships that were highlighted in Chapter 3 and Chapter 4 (Objective 3).

Chapter 6 discusses the results obtained from the previous chapters and how they contribute to previously identified knowledge gaps. Also, some future research suggestions and several policy recommendations are mentioned here.

Bibliography

Adinugroho, W., Suryadiputra, N., Saharjo, B. and Siboro, L. 2005. *MANUAL for the CONTROL of Fire in Peatlands and Peatland Forest.*

Albar, I. 2015. Typology Analysis of Land and Forest Fire in Riau Province, Indonesia. In: *International Workshop on Land Use/Cover Change and Air Pollution, 4-7 August 2015, Bogor*.

Andela, N., Morton, D.C., Giglio, L., Chen, Y., van der Werf, G.R., Kasibhatla, P.S., DeFries, R.S., Collatz, G.J., Hantson, S., Kloster, S., Bachelet, D., Forrest, M., Lasslop, G., Li, F., Mangeon, S., Melton, J.R., Yue, C. and Randerson, J.T. 2017. A human-driven decline in global burned area. *Science.* **356**(6345), p1356.

Andela, N., Morton, D.C., Giglio, L., Paugam, R., Chen, Y., Hantson, S., van der Werf, G.R. and Randerson, J.T. 2019. The Global Fire Atlas of individual fire size, duration, speed and direction. *Earth Syst. Sci. Data.* **11**(2), pp.529-552.

Andriesse, J.P. 1988. *Nature and management of tropical peat soils.* [Online]. Food and Agriculture Organization of the United Nations. Available from: http://www.fao.org/3/x5872e/x5872e00.htm

Anggoro. 2016. *Saksi Ahli Dishutbun Pelalawan: Kebakaran PT LIH Karena Api Lompat.* [Online]. Available from: https://riau.antaranews.com/berita/70206/saksi-ahli-dishutbun-pelalawan-kebakaran-pt-lih-karena-api-lompat

Applegate, G., Chokkalingam, U. and Suyanto, S. 2001. *The Underlying Causes and Impacts of Fires in South-East Asia—final report.*

Austin, K.G., Schwantes, A., Gu, Y. and Kasibhatla, P.S. 2019. What causes deforestation in Indonesia? *Environmental Research Letters.* **14**(2), p024007.

Barbosa, P., Caetano, M.R. and Santos, T.G. 2000. Detection of changes in forest landcover type after fires in Portugal. *International Archieves of Photogrammetry and Remote Sensing.* (XXXIII).

BBC. 2019. *Asap kebakaran hutan di Jambi 'membuat langit menjadi merah'.* [Online]. [Accessed 25 June 2020]. Available from: https://www.bbc.com/indonesia/indonesia-49787843

Bowen, M.R., Bompard, J.M., Anderson, I.P., Guizol, P. and Gouyon, A. 2001. *Anthropogenic fires in Indonesia: a view from Sumatra.* Huntington, New York: Nova Science Publishers.

Bowman, D.M.J.S., Balch, J.K., Artaxo, P., Bond, W.J., Carlson, J.M., Cochrane, M.A., D'Antonio, C.M., Defries, R.S., Doyle, J.C., Harrison, S.P., Johnston, F.H., Keeley, J.E., Krawchuk, M.A., Kull, C.A., Marston, J.B., Moritz, M.A., Prentice, I.C., Roos, C.I., Scott, A.C., Swetnam, T.W., van Der Werf, G.R. and Pyne, S.J. 2009. Fire in the Earth system. *Science (New York, N.Y.).* **324**(5926), pp.481-484.

Brandt, J., Primdahl, J. and Reenberg, A. 1999. Rural land-use and landscape dynamics - analysis of 'driving forces' in space and time. In: Krönert, R., et al. eds. *Land-use changes and their environmental impact in rural areas in Europe.* Paris: Unesco, pp.81-102.

Wildfire. s.v.

Bürgi, M., Hersperger, A.M. and Schneeberger, N. 2004. Driving forces of landscape change - current and new directions. *Landscape Ecology.* **19**(8), pp.857-868.

Cochrane, M.A. 2003. Fire science for rainforests. *Nature.* **421**(6926), pp.913-919.

Cochrane, M.A. 2009. Fire in the tropics. In: Cochrane, M.A. ed. *Tropical Fire Ecology: Climate Change, Land Use, and Ecosystem Dynamics.* Berlin, Heidelberg: Springer Berlin Heidelberg, pp.1-23.

Cochrane, M.A. and Schulze, M.D. 1999. Fire as a Recurrent Event in Tropical Forests of the Eastern Amazon: Effects on Forest Structure, Biomass, and Species Composition. *Biotropica.* **31**(1), pp.2-16.

Countryman, C.M. 1972. *The fire environment concept.* Berkeley, CA: USDA Forest Service, Pacific Southwest Forest and Range Experiment Station.

Crippa, P., Castruccio, S., Archer-Nicholls, S., Lebron, G.B., Kuwata, M., Thota, A., Sumin, S., Butt, E., Wiedinmyer, C. and Spracklen, D.V. 2016. Population exposure to hazardous air quality due to the 2015 fires in Equatorial Asia. *Sci Rep.* **6**, p37074.

Dennis, R.A., Mayer, J., Applegate, G., Chokkalingam, U., Colfer, C., Kurniawan, I., Lachowski, H., Maus, P., Permana, R.P., Ruchiat, Y., Stolle, F., Suyanto and Tomich, T.P. 2005. Fire, People and Pixels: Linking Social Science and Remote Sensing to Understand Underlying Causes and Impacts of Fires in Indonesia. *Human Ecology.* **33**(4), pp.465-504.

Dohong, A., Aziz, A.A. and Dargusch, P. 2017. A review of the drivers of tropical peatland degradation in South-East Asia. *Land Use Policy.* **69**(Supplement C), pp.349-360.

Ekadinata, A.E. and Dewi, S. 2011. *Estimating losses in aboveground carbon stock from land-use and land-cover changes in Indonesia (1990, 2000, 2005).* Bogor: World Agroforestry Centre (ICRAF) Southeast Asia Program.

Eva, H. and Lambin, E.F. 2000. Fires and Land-Cover Change in the Tropics: A Remote Sensing Analysis at the Landscape Scale. *Journal of Biogeography.* **27**(3), pp.765-776.

Fanin, T. and van der Werf, G.R. 2015. Relationships between burned area, forest cover loss, and land cover change in the Brazilian Amazon based on satellite data. *Biogeosciences.* **12**(20), pp.6033-6043.

Fanin, T. and van der Werf, G.R. 2017. Precipitation–fire linkages in Indonesia (1997–2015). *Biogeosciences.* **14**(18), pp.3995-4008.

Field, R.D., van der Werf, G.R., Fanin, T., Fetzer, E.J., Fuller, R., Jethva, H., Levy, R., Livesey, N.J., Luo, M., Torres, O. and Worden, H.M. 2016. Indonesian fire activity and smoke pollution in 2015 show persistent nonlinear sensitivity to El Nino-induced drought. *Proc Natl Acad Sci U S A.* **113**(33), pp.9204-9209.

Field, R.D., van der Werf, G.R. and Shen, S.S.P. 2009. Human amplification of drought-induced biomass burning in Indonesia since 1960. *Nature Geosci.* **2**(3), pp.185-188.

Gaveau, D.L., Salim, M.A., Hergoualc'h, K., Locatelli, B., Sloan, S., Wooster, M., Marlier, M.E., Molidena, E., Yaen, H., DeFries, R., Verchot, L., Murdiyarso, D., Nasi, R., Holmgren, P. and Sheil, D. 2014. Major atmospheric emissions from peat fires in Southeast Asia during non-drought years: evidence from the 2013 Sumatran fires. *Sci Rep.* **4**, p6112.

Gaveau, D.L.A., Sheil, D., Husnayaen, Salim, M.A., Arjasakusuma, S., Ancrenaz, M., Pacheco, P. and Meijaard, E. 2016. Rapid conversions and avoided deforestation: examining four decades of industrial plantation expansion in Borneo. *Scientific Reports.* **6**, p32017.

Goldammer, J.G. 2013. *Vegetation Fires and Global Change*. Kessel Publishing. Available from: https://gfmc.online/wp-content/uploads/Vegetation-Fires-Global-Change-UN-White-Paper-GFMC-2013.pdf

Greenpeace. 2013. *An Impending Storm - Impact of Deforestation on Weather Patterns and Agriculture.pdf>.*

GSARS.org. 2016. *Information on Land in the Context of Agricultural Statistisc.*

Hansen, M.C., Defries, R.S., Townshend, J.R.G. and Sohlberg, R. 2000. Global land cover classification at 1 km spatial resolution using a classification tree approach. *International Journal of Remote Sensing.* **21**(6-7), pp.1331-1364.

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O. and Townshend, J.R. 2013. High-resolution global maps of 21st-century forest cover change. *Science.* **342**(6160), pp.850-853.

Hansen, M.C., Stehman, S.V. and Potapov, P.V. 2010. Quantification of global gross forest cover loss. *Proc Natl Acad Sci U S A.* **107**(19), pp.8650-8655.

Harja, D., Dewi, S., Heryawan, F. and van Noordwijk, M. 2011. *Forest carbon-stock estimates based on National Forest Inventory data.*

Harris, N.L., Goldman, E., Gabris, C., Nordling, J., Minnemeyer, S., Ansari, S., Lippmann, M., Bennett, L., Raad, M., Hansen, M. and Potapov, P. 2017. Using spatial statistics to identify emerging hot spots of forest loss. *Environmental Research Letters.* **12**(2), p024012.

Harrison, M., Page, S. and Limin, S. 2009. The global impact of Indonesian forest fires. *Biologist.* **56**, pp.156-163.

Harrison, M.E., Ottay, J.B., D'Arcy, L.J., Cheyne, S.M., Anggodo, Belcher, C., Cole, L., Dohong, A., Ermiasi, Y., Feldpausch, T., Gallego-Sala, A., Gunawan, A., Höing, A., Husson, S.J., Kulu, I.P., Soebagio, S.M., Mang, S., Mercado, L., Morrogh-Bernard, H.C., Page, S.E., Priyanto, R., Ripoll Capilla, B., Rowland, L., Santos, E.M., Schreer, V., Sudyana, I.N., Taman, S.B.B., Thornton, S.A., Upton, C., Wich, S.A. and van Veen, F.J.F. 2019. Tropical forest and peatland conservation in Indonesia: Challenges and directions. *People and Nature.* **n/a**(n/a).

Hersperger, A.M., Gennaio, M.-P., Verburg, P.H. and Bürgi, M. 2010. Linking Land Change with Driving Forces and Actors: Four Conceptual Models. *Ecology and Society.* **15**(4).

Huijnen, V., Wooster, M.J., Kaiser, J.W., Gaveau, D.L.A., Flemming, J., Parrington, M., Inness, A., Murdiyarso, D., Main, B. and van Weele, M. 2016. Fire carbon emissions over maritime southeast Asia in 2015 largest since 1997. *Scientific Reports.* **6**, p26886.

Izquierdo, N.L. 2017. *Formation of tropical peatlands.* [Online]. Available from: https://www.grida.no/resources/12531

James, S.R., Dennell, R.W., Gilbert, A.S., Lewis, H.T., Gowlett, J.A.J., Lynch, T.F., McGrew, W.C., Peters, C.R., Pope, G.G. and Stahl, A.B. 1989. Hominid Use of Fire in the Lower and Middle Pleistocene: A Review of the Evidence [and Comments and Replies]. *Current Anthropology.* **30**(1), pp.1-26.

Jayarathne, T., Stockwell, C., Gilbert, A., Daugherty, K., Cochrane, M., Ryan, K., Putra, E., Saharjo, B., Dwi Nurhayati, A., Albar, I., Yokelson, R. and Stone, E. 2018. Chemical characterization of fine particulate matter emitted by peat fires in Central Kalimantan, Indonesia, during the 2015 El Niño. *Atmospheric Chemistry and Physics.* **18**, pp.2585-2600.

Joosten, H. and Clarke, D. 2002. *Wise Use of Mires and Peatlands.* International Mire Conservation Group and International Peat Society.

Juárez-Orozco, S.M., Siebe, C. and Fernández y Fernández, D. 2017. Causes and Effects of Forest Fires in Tropical Rainforests: A Bibliometric Approach. *Tropical Conservation Science.* **10**, p1940082917737207.

Keenan, R., Reams, G., Frédéric, A., Freitas, J.V., Grainger, A. and Lindquist, E. 2015. Dynamics of global forest area: Results from the FAO

Global Forest Resources Assessment 2015. *Forest Ecology and Management.* **352**.

Kiely, L., Spracklen, D.V., Wiedinmyer, C., Conibear, L., Reddington, C.L., Archer-Nicholls, S., Lowe, D., Arnold, S.R., Knote, C., Khan, M.F., Latif, M.T., Kuwata, M., Budisulistiorini, S.H. and Syaufina, L. 2019. New estimate of particulate emissions from Indonesian peat fires in 2015. *Atmos. Chem. Phys.* **19**(17), pp.11105-11121.

Kinnaird, M. and O'Brien, T. 1998. Ecological effects of wildfire on lowland rainforest in Sumatra. *Conservation Biology.* **12**, pp.954-956.

Koplitz, S.N., Mickley, L.J., Marlier, M.E., Buonocore, J.J., Kim, P.S., Liu, T., Sulprizio, M.P., DeFries, R.S., Jacob, D.J., Schwartz, J., Pongsiri, M. and Myers, S.S. 2016. Public health impacts of the severe haze in Equatorial Asia in September–October 2015: demonstration of a new framework for informing fire management strategies to reduce downwind smoke exposure. *Environmental Research Letters.* **11**(9), p094023.10.1088/1748-9326/11/9/094023

Langner, A., Miettinen, J. and Siegert, F. 2007. Land cover change 2002–2005 in Borneo and the role of fire derived from MODIS imagery. *Global Change Biology.* **13**(11), pp.2329-2340.

Langner, A. and Siegert, F. 2009. Spatiotemporal fire occurrence in Borneo over a period of 10 years. *Global Change Biology.* **15**(1), pp.48-62.

Lappalainen. 1996. *Global Peat Map.* [Online]. Available from: https://peatlands.org/peatlands/where-can-peatlands-be-found/

Lavorel, S., Flannigan, M.D., Lambin, E.F. and Scholes, M.C. 2006. Vulnerability of land systems to fire: Interactions among humans, climate, the atmosphere, and ecosystems. *Mitigation and Adaptation Strategies for Global Change.* **12**(1), pp.33-53.

Margono, B.A., Potapov, P.V., Turubanova, S., Stolle, F. and Hansen, M.C. 2014. Primary forest cover loss in Indonesia over 2000–2012. *Nature Climate Change.* **4**(8), pp.730-735.

Marlier, M.E., DeFries, R.S., Kim, P.S., Koplitz, S.N., Jacob, D.J., Mickley, L.J. and Myers, S.S. 2015. Fire emissions and regional air quality impacts from fires in oil palm, timber, and logging concessions in Indonesia. *Environmental Research Letters.* **10**(8), p085005.

Marlier, M.E., DeFries, R.S., Voulgarakis, A., Kinney, P.L., Randerson, J.T., Shindell, D.T., Chen, Y. and Faluvegi, G. 2013. El Niño and health risks from landscape fire emissions in Southeast Asia. *Nature climate change.* **3**, pp.131-136.

Miettinen, J. and Liew, S.C. 2005. Connection between fire and land cover change in Southeast Asia: a remote sensing case study in Riau, Sumatra. *International Journal of Remote Sensing.* **26**(6), pp.1109-1126.

Mitchard, E.T.A. 2018. The tropical forest carbon cycle and climate change. *Nature.* **559**(7715), pp.527-534.

Moritz, M.A., Morais, M.E., Summerell, L.A., Carlson, J.M. and Doyle, J. 2005. Wildfires, complexity, and highly optimized tolerance. *Proceedings of the National Academy of Sciences of the United States of America.* **102**(50), p17912.

Mouillot, F. and Field, C.B. 2005. Fire history and the global carbon budget: a 1°× 1° fire history reconstruction for the 20th century. *Global Change Biology.* **11**(3), pp.398-420.

Msofe, N.K., Sheng, L. and Lyimo, J. 2019. Land Use Change Trends and Their Driving Forces in the Kilombero Valley Floodplain, Southeastern Tanzania. *Sustainability.* **11**(2).

Murdiyarso, D. and Lebel, L. 2007a. Local to global perspectives on forest and land fires in Southeast Asia. *Mitigation and Adaptation Strategies for Global Change.* **12**(1), pp.3-11.

Murdiyarso, D. and Lebel, L. 2007b. Southeast Asian Fire Regimes and Land Development Policy. pp.261-271.

Murdiyarso, D. and Lebel, L. 2007c. Southeast Asian Fire Regimes and Land Development Policy. In: Canadell, J.G., et al. eds. *Terrestrial Ecosystems in a Changing World.* Berlin, Heidelberg: Springer Berlin Heidelberg, pp.261-271.

Nurrochmat, D.R. and Abdullah, L. 2014. Memanfaatkan Hutan Mengurangi Emisi. *Risalah Kebijakan Pertanian dan Lingkungan.* **1**(1), pp.18-13.

Nurrochmat, D.R., Darusman, D. and Ekayani, M. 2016. *Kebijakan Pembangunan Kehutanan dan Lingkungan. Teori dan Implentasi.* Bogor: IPB Press.

Olson, D.M., Dinerstein, E., Wikramanayake, E.D., Burgess, N.D., Powell, G.V.N., Underwood, E.C., D'Amico, J.A., Itoua, I., Strand, H.E., Morrison, J.C., Loucks, C.J., Allnutt, T.F., Ricketts, T.H., Kura, Y., Lamoreux, J.F., Wettengel, W.W., Hedao, P. and Kassem, K.R. 2001. Terrestrial Ecoregions of the World: A New Map of Life on Earth: A new global map of terrestrial ecoregions provides an innovative tool for conserving biodiversity. *BioScience.* **51**(11), pp.933-938.

Page, S.E., Banks, C. and Rieley, J. 2007. Tropical peatlands: Distribution, extent and carbon storage-uncertainties and knowledge gaps. **2**.

Page, S.E., Hoscilo, A., Langner, A., Tansey, K., Siegert, F., Limin, S. and Rieley, J. 2009. Tropical peatland fires in Southeast Asia. In: Cochrane, M.A. ed. *Tropical Fire Ecology: Climate Change, Land Use, and Ecosystem Dynamics.* Berlin, Heidelberg: Springer Berlin Heidelberg, pp.263-287.

Page, S.E., Hoscilo, A., Wösten, H., Jauhiainen, J., Silvius, M., Rieley, J., Ritzema, H., Tansey, K., Graham, L., Vasander, H. and Limin, S. 2008.

Restoration Ecology of Lowland Tropical Peatlands in Southeast Asia: Current Knowledge and Future Research Directions. *Ecosystems.* **12**(6), pp.888-905.

Page, S.E., Rieley, J., Hoscilo, A., Spessa, A. and Weber, U. 2013. Current Fire Regimes, Impacts and the Likely Changes – IV: Tropical Southeast Asia Introduction. *Vegetation Fires and Global Changes - Challanges for Concerted International Action.*

Page, S.E., Rieley, J. and Wüst, R. 2006. Chapter 7 Lowland tropical peatlands of Southeast Asia. *Peatlands: Evolution and Records of Environmental and Climate Changes.* **9**.

Page, S.E., Rieley, J.O. and Banks, C.J. 2011. Global and regional importance of the tropical peatland carbon pool. *Global Change Biology.* **17**(2), pp.798-818.

Page, S.E., Siegert, F., Rieley, J.O., Boehm, H.D., Jaya, A. and Limin, S. 2002. The amount of carbon released from peat and forest fires in Indonesia during 1997. *Nature.* **420**(6911), pp.61-65.

Pielke Sr, R.A., Pitman, A., Niyogi, D., Mahmood, R., McAlpine, C., Hossain, F., Goldewijk, K.K., Nair, U., Betts, R., Fall, S., Reichstein, M., Kabat, P. and de Noblet, N. 2011. Land use/land cover changes and climate: modeling analysis and observational evidence. *WIREs Climate Change.* **2**(6), pp.828-850.

Prabowo, D., Maryudi, A., Senawi and Imron, M.A. 2017. Conversion of forests into oil palm plantations in West Kalimantan, Indonesia: Insights from actors' power and its dynamics. *Forest Policy and Economics.* **78**, pp.32-39.

Prasetyo, L.B., Dharmawan, A.H., Nasdian, F.T. and Ramdhoni, S. 2016. Historical Forest fire Occurrence Analysis in Jambi Province During the Period of 2000 – 2015: Its Distribution & Land Cover Trajectories. *Procedia Environmental Sciences.* **33**, pp.450-459.

Prayoto, Ishihara, M.I., Firdaus, R. and Nakagoshi, N. 2017. Peatland Fires in Riau, Indonesia, in Relation to Land Cover Type, Land Management, Landholder, and Spatial Management. *Journal of Environmental Protection.* **08**(11), pp.1312-1332.

Prayoto, T. 2011. Analysis of Forest and Land Fires in Riau Province Based on the Use of Land for Mitigation of Smoke Disaster Analysis. In: *International Conference of Indonesian Forestry Researchers (INAFOR), Bogor*.

Purnomo, H., Shantiko, B., Sitorus, S., Gunawan, H., Achdiawan, R., Kartodihardjo, H. and Dewayani, A.A. 2017. Fire economy and actor network of forest and land fires in Indonesia. *Forest Policy and Economics.* **78**, pp.21-31.

Putra, E.I., Cochrane, M.A., Saharjo, B.H., Graham, L., Thomas, A., Applegate, G., Saad, A., Setianto, E., Sutikno, S. and Prayitno, A. 2019.

Developing better understanding on tropical peat fire occurrences and dynamics. *IOP Conference Series: Earth and Environmental Science.* **394**, p012044.

Pyne, S.J. 2019. *Fire A Brief History.* 2nd ed. Seattle: University of Washington Press.

Reddington, C.L., Yoshioka, M., Balasubramanian, R., Ridley, D., Toh, Y.Y., Arnold, S.R. and Spracklen, D.V. 2014. Contribution of vegetation and peat fires to particulate air pollution in Southeast Asia. *Environmental Research Letters.* **9**(9), p094006.

Rieley, J.O., Ahmad-Shah, A.A. and Brady, M.A. 1996. *The extent and nature of tropical peat swamps.* Cardigan: IUCN.

Rijal, S., Saleh, M.B., Jaya, I.N.S. and Tiryana, T. 2016. *Deforestation Profile of Regency Level in Sumatra.*

Saatchi, S.S., Harris, N.L., Brown, S., Lefsky, M., Mitchard, E.T.A., Salas, W., Zutta, B.R., Buermann, W., Lewis, S.L., Hagen, S., Petrova, S., White, L., Silman, M. and Morel, A. 2011. Benchmark map of forest carbon stocks in tropical regions across three continents. *Proceedings of the National Academy of Sciences.* **108**(24), p9899.

Saharjo, B.H. 1997. Fire protection and industrial plantation management in the Tropics. *The Commonwealth Forestry Review.* **76**(3), pp.203-206.

Schoene, D., Killmann, W., von Lüpke, H. and Loychewilkie, M. 2007. *Definitional issues related to reducing emissions from deforestation in developing countries.*

Scott, A.C., Bowman, D.M.J.S., Bond, W.J., Pyne, S.J. and Alexander, M.E. 2014. *Fire on Earth : An Introduction.* Hoboken, UNITED KINGDOM: John Wiley & Sons, Incorporated.

Setiawan, E.N., Maryudi, A., Purwanto, R.H. and Lele, G. 2016. Opposing interests in the legalization of non-procedural forest conversion to oil palm in Central Kalimantan, Indonesia. *Land Use Policy.* **58**, pp.472-481.

Sloan, S., Locatelli, B., Wooster, M.J. and Gaveau, D.L.A. 2017. Fire activity in Borneo driven by industrial land conversion and drought during El Niño periods, 1982–2010. *Global Environmental Change.* **47**, pp.95-109.

Song, X.-P., Hansen, M.C., Stehman, S.V., Potapov, P.V., Tyukavina, A., Vermote, E.F. and Townshend, J.R. 2018. Global land change from 1982 to 2016. *Nature.* **560**(7720), pp.639-643.

Stockwell, C.E., Jayarathne, T., Cochrane, M.A., Ryan, K.C., Putra, E.I., Saharjo, B.H., Nurhayati, A.D., Albar, I., Blake, D.R., Simpson, I.J., Stone, E.A. and Yokelson, R.J. 2016. Field measurements of trace gases and aerosols emitted by peat fires in Central Kalimantan, Indonesia, during the 2015 El Niño. *Atmos. Chem. Phys.* **16**(18), pp.11711-11732.

Suyanto, Applegate, G., Permana, R.P., Khususiyah, N. and Kurniawan, I. 2004. The Role of Fire in Changing Land Use and Livelihoods in Riau - Sumatera.pdf. *Ecology and Society.* **9**(1), p15.

Taufik, M., Torfs, P.J.J.F., Uijlenhoet, R., Jones, P.D., Murdiyarso, D. and Van Lanen, H.A.J. 2017. Amplification of wildfire area burnt by hydrological drought in the humid tropics. *Nature Climate Change.* **7**, p428.

Torero, J.L. 2013. An Introduction to Combustion in Organic Materials. *Fire Phenomena and the Earth System.* pp.1-13.

Trimble, M. and van Aarde, R. 2012. Geographical and taxonomic biases in research on biodiversity in human-modified landscapes. *Ecosphere.* **3**, part119.

TWB. 2016. *The Cost of Fire: An Economic Analysis of Indonesia's 2015 Fire Crisis;.* Jakarta: The World Bank.

USGS. *How do changes in climate and land use relate to one another?* [Online]. Available from: https://www.usgs.gov/faqs/how-do-changes-climate-and-land-use-relate-one-another-1?

Usup, A., Huashimoto, Y., Takahashi, H. and Hayasaka, H. 2004. Combustion and thermal characteristic of peat fire in tropical peatland in Central Kalimantan, Indonesia. *Tropics.* **14**, pp.1-19.

van der Werf, G.R., Dempewolf, J., Trigg, S.N., Randerson, J.T., Kasibhatla, P.S., Giglio, L., Murdiyarso, D., Peters, W., Morton, D.C., Collatz, G.J., Dolman, A.J. and DeFries, R.S. 2008. Climate regulation of fire emissions and deforestation in equatorial Asia. *Proc Natl Acad Sci U S A.* **105**(51), pp.20350-20355.

van der Werf, G.R., Randerson, J.T., Collatz, G.J. and Giglio, L. 2003. Carbon emissions from fires in tropical and subtropical ecosystems. *Global Change Biology.* **9**(4), pp.547-562.

Vayda, A.P. 2006. Causal Explanation of Indonesian Forest Fires: Concepts, Applications, and Research Priorities. *Human Ecology.* **34**(5), pp.615-635.

Vetrita, Y. and Cochrane, M.A. 2020. Fire Frequency and Related Land-Use and Land-Cover Changes in Indonesia's Peatlands. *Remote Sensing.* **12**(1).

Wüst, R., Rieley, J., Page, S., van der Kaars, S. and Wang, W.-M. 2007. Peatland evolution in Southeast Asia during the last 35,000cal years: implications for evaluating their carbon storage potential.

WWF. 2015. *Saving Forests at Risk.* WWF.

Yeager, C., Marshall, A., Stickler, C. and Chapman, C. 2003. Effects of forest fires on peat swamp and lowland Dipterocarp forests in Kalimantan, Indonesia. *Tropical Biodiversity.* **8**, pp.121–138.

Chapter 2

Data and Methods

This chapter describes the study area regarding its climate characteristics, geography and biodiversity condition, social economy profile and legal situation. Also included in this chapter is an explanation of the data used in this research such as administrative boundary, fire hotspots, land use, land cover and land type. The last section in this chapter describes the data processing steps.

2.1 Study Area

Our study area is Riau Province, Indonesia, situated in central eastern coast of Sumatra Island, facing the Strait of Malacca and adjacent to Singapore and Malaysia. Riau covers a geographic area extending between 100°00’ – 105°05’ E and 01°05’ and 02°25’ S, covering 8.9 Mha where 6 million people live (Figure 2.1).

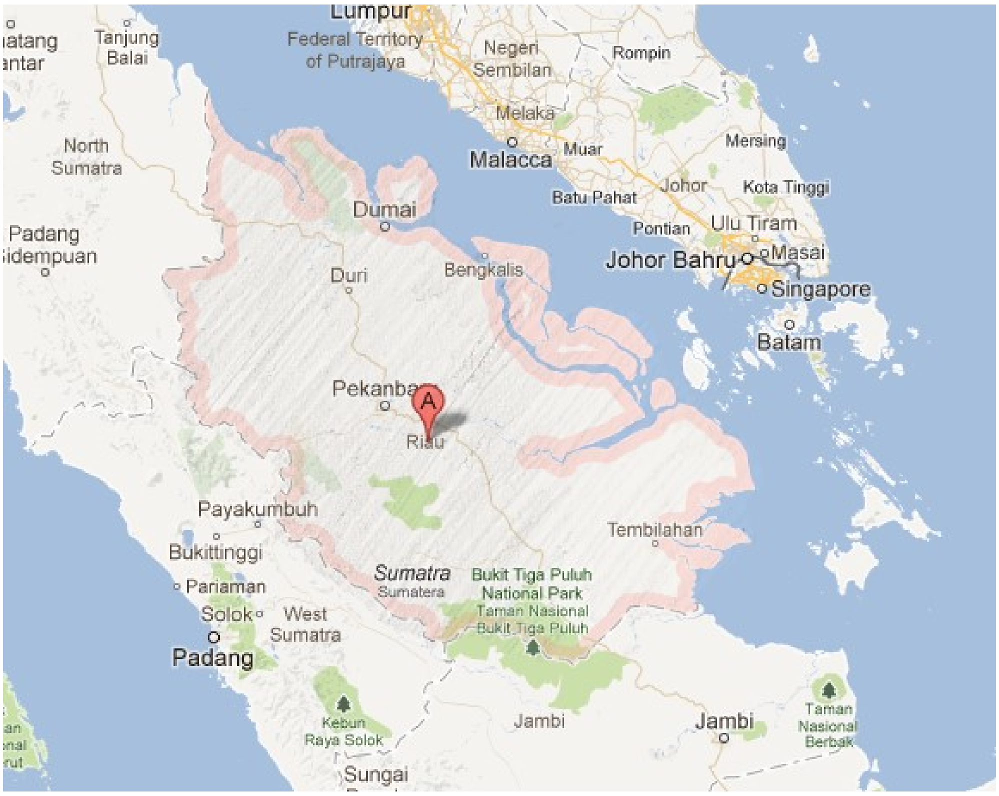


Figure 2.1 Map of Riau Province
(Regional Goverment of Riau Province, 2020).

2.1.1 Climate Characteristics

The entire Riau Province falls into the Af class of Köppen and Geiger classification, meaning the tropical rainforest climate type which has a significant amount of rainfall throughout the year even in the driest month (Climate-Data.org). Also, Figure 2.2 shows that Riau is in climate Region B which has two rainfall peaks, in October–November (ON) and in March to May (MAM) in association with the southward and northward movement of the inter-tropical convergence zone (Aldrian and Susanto, 2003).

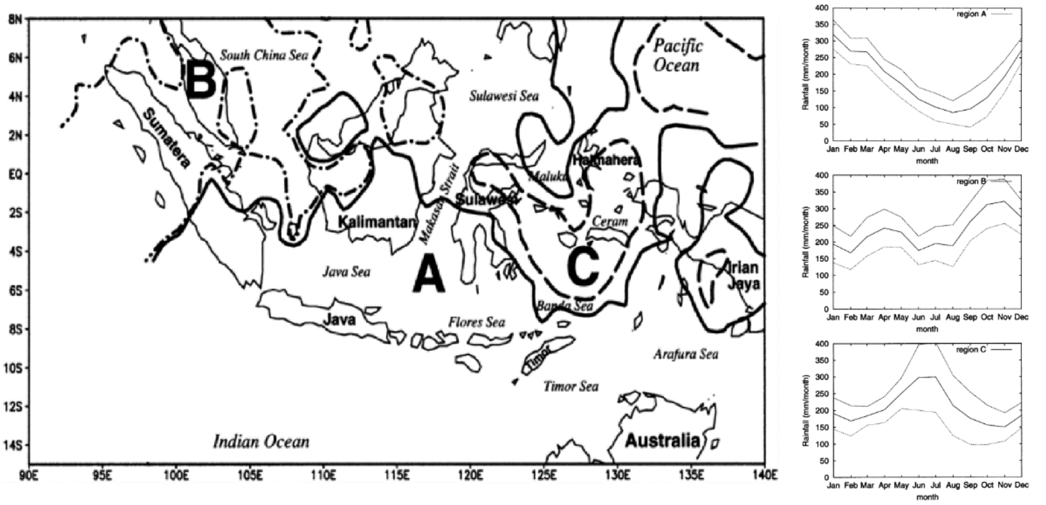


Figure 2.2 Indonesia Climate Regions (Aldrian and Susanto, 2003).

2.1.2 Geography and Biodiversity Condition

Wahyunto et al. (2014) reported Riau Province consisted of 3.86 Mha (43%) peatland, equal to 60% of peatland coverage in Sumatra Island (6.4 Mha) or 26% of Indonesia peatland (14.9 Mha). There are four big rivers in Riau which cut across from the Bukit Barisan mountainous area to the Malacca Strait (Regional Goverment of Riau Province, 2020):

- The Siak River (300 km) with 8 - 12 m depth,
- The Rokan River (400 km) with 6 - 8 m depth,
- The Kampar River (400 km) with 6 m depth
- The Indragiri River (500 km) with 6 - 8 m depth

In Pelalawan district, there is Tesso Nilo National Park (TNNP) which is the home for abundant species including at least 360 flora, 107 birds, 23 mammals (including elephant and tiger), 3 primate, 50 fish, 15 reptiles and 18 amphibia. TNNP covers 38 576 hectares when established in 2004 and was expanded to 81 793 ha in 2008 (TNNP, 2019). Since TNPP contains exceptional concentrations of species including endemics representing

Sumatran islands lowland and montane forests (Gillison, 2001; Prawiradilaga et al., 2014), it is included in the global 200 priority ecoregions for conservation (Olson and Dinerstein, 2002). Some efforts has been made to integrate TNPP with neighbourhood conservation (Bukit Tiga Puluh National Park, Bukit Rimbang Protected Area, Bukit Baling Protected Area, Bukit Bungkuk Protected Area and Kerumutan Protected Area) as Tesso Nilo Bukit Tigapuluh Landscape (Figure 2.3) which will covers about 2 millions hectares.

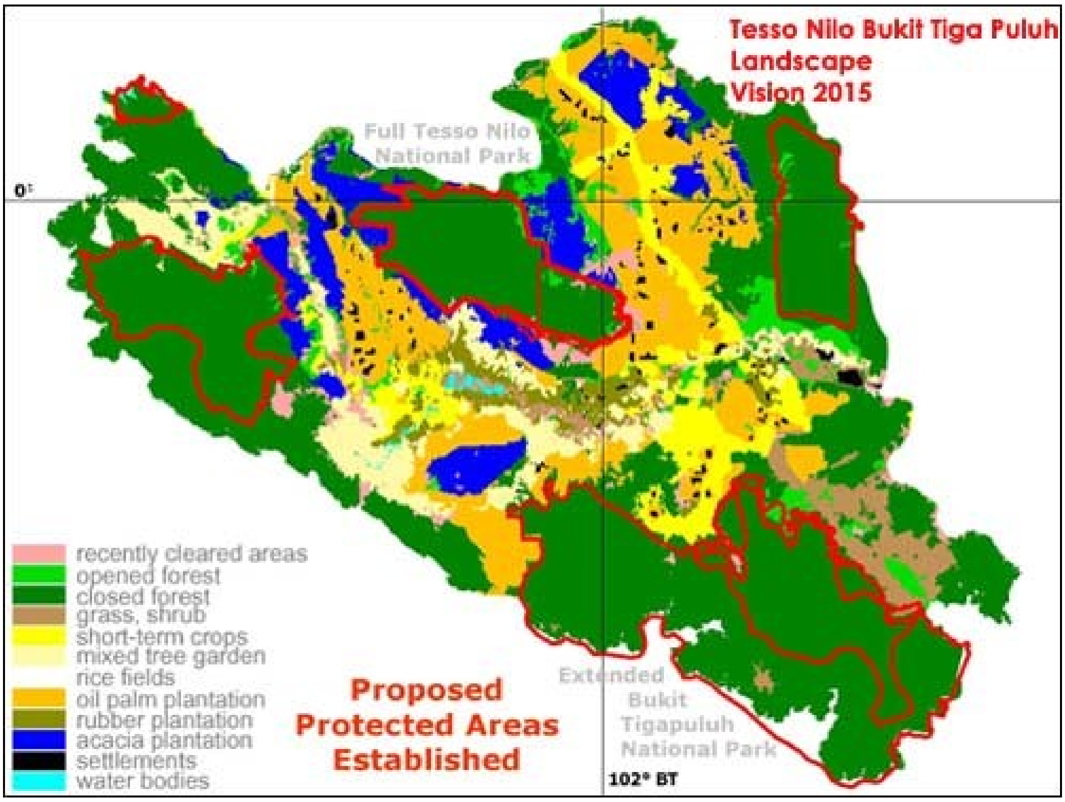


Figure 2.3 Proposed Tesso Nilo Bukit Tigapuluh Landscape (WWF Indonesia).

2.1.3 Social Economy Profile

In the early 1970s, Riau was still covered with extensive forest areas with over 95% of the province classified as state forest area at that time (Ministry of Forestry of the Republic of Indonesia 1986). Figure 2.4 shows the east part of Riau province still covered by forest in 1999. Since then, Riau has experienced rapid expansion of forestry concessions (IUPHHK-HA / HPH) (Figure 2.5) and development of industrial timber plantations (IUPHHK-HT / HTI) (Figure 2.6). Agriculture (including forestry) is now a very important sector in this province, contributing approximately 20% of Gross Regional Domestic Product and accounting for 46% of the workforce. Oil palm plantations are important for development as they may decrease poverty in rural areas (Bappenas, 2015), providing economic benefits for around 2.6 million Indonesians (Edwards, 2019). Figure 2.7 shows the extent of area granted for IUPHHK-HA (2004-2019) and IUPHHK-HTI (2011-2019). Figure 2.8 shows the expansion of oil palm concession between 1996 and 2019 in this province.

Table 2.1 shows log production from forest concessions increased substantially in 2018 (586 508 m^3) compared to <60 000 m^3 between 2014-2017. Over the same period the output of timber companies slowly increased from around 15 000 m^3 to 20 000 m^3 between 2014 and 2018. Around 4 million ton of pulp produced every year whilst plywood industry output was 95 000 m^3 year^{-1} and sawn timber was 55 m^3 year^{-1} (BPS Riau, 2020).

Table 2.1 Timber Production by Type of Product (m^3) 2014-2018 as logs (above) and processed timber (below) (BPS Riau, 2020).

Tahun *Year*	Kayu Bulat *Logs (m3)*			
	IUPHHK-HA *Forest Concession Establishment*	IUPHHK-HT *Timber Establishment*	Perum Perhutani *State Enterprises*	Jumlah *Total*
(1)	(2)	(3)	(4)	(5)
2014	57 307,00	15 538 941,00	...	15 596 248,00
2015	35 587,00	14 126 049,00	...	14 161 637,00
2016	30 159,00	16 991 099,00	...	17 021 258,00
2017	39 717,00	19 922 579,00	...	19 962 296,00
2018	586 508,00	19 965 510,00	...	20 552 018,00

Tahun *Year*	Kayu Olahan *Processed Timber*				
	Kayu Gergajian *Sawn Timber (m3)*	Kayu Lapis *Plywood (m3)*	Bubur Kayu *Pulp (Ton)*	Serpih Kayu *Wood Flakes (m3)*	Veneer *Veneers (m3)*
(1)	(6)	(7)	(8)	(9)	(10)
2014	46 996,51	116 331,00	4 218 947,00	17 598 028,00	–
2015	56 709,71	117 685,00	4 364 377,00	18 490 454,00	–
2016	47 519,71	103 384,00	4 398 795,00	18 453 548,00	–
2017	56 609,96	77 637,00	4 121 500,00	18 672 663,00	255
2018	70 360,48	63 827,00	4 001 383,00	17 469 836,00	3 927,00

Catatan/*Note*: ...
Sumber/*Source*: Kementerian Lingkungan Hidup dan Kehutanan/ *Ministry of Environment and Forestry*

s://riau.bps.go.id

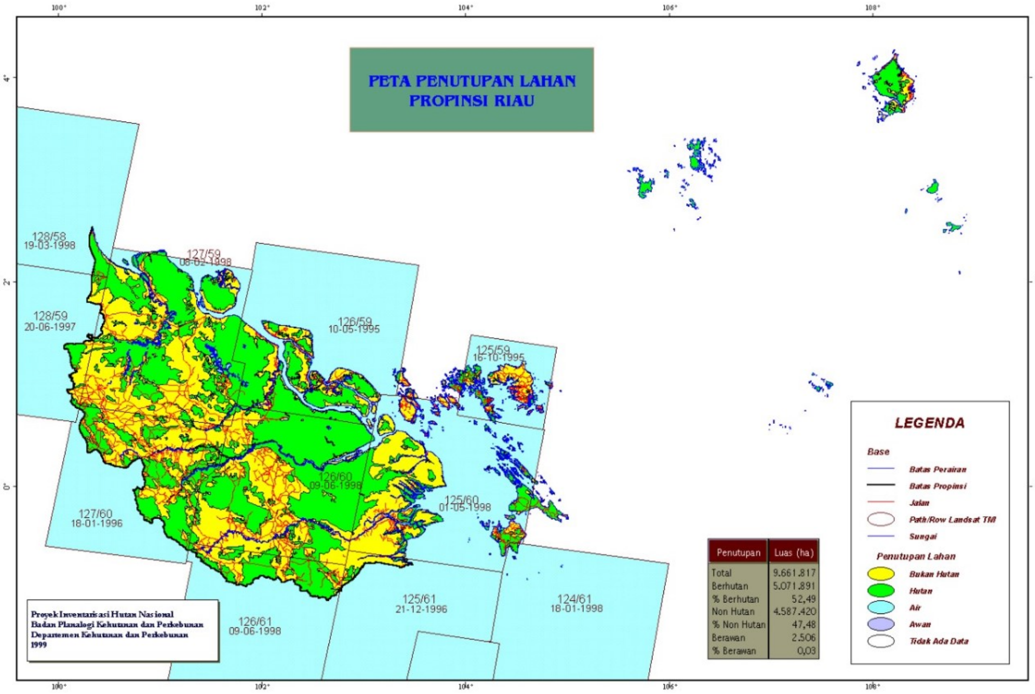


Figure 2.4 Map of Land Cover in 1999 (MoF, 2002) as non-forest (yellow), forest (green), water (light blue) and cloud (purple).

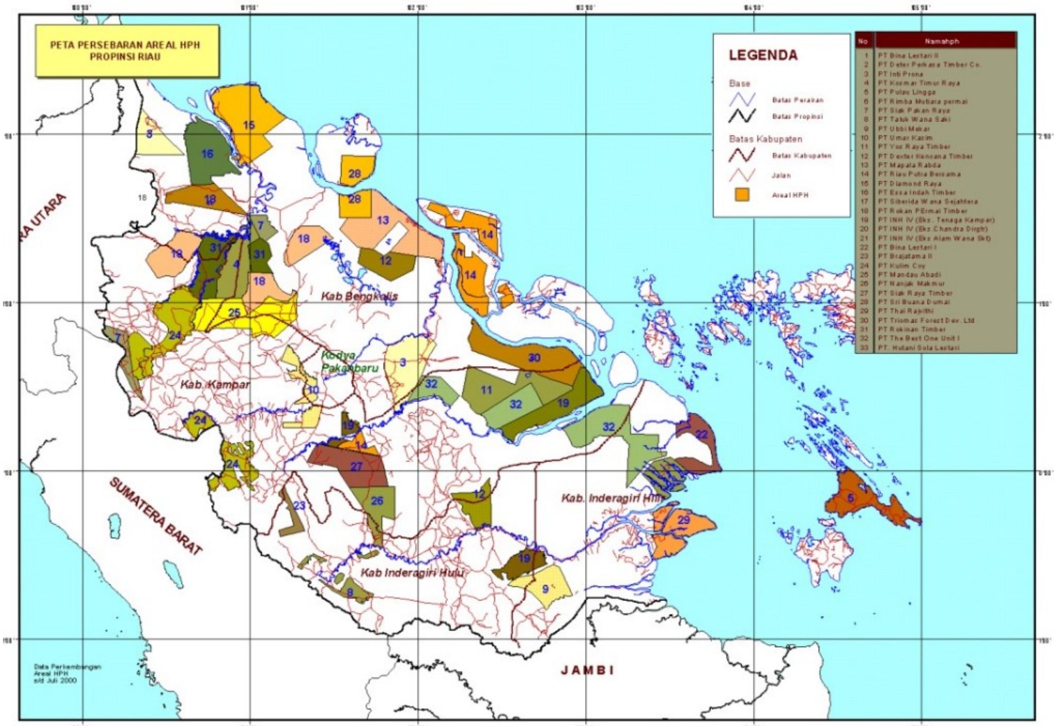


Figure 2.5 Map of Commercial Forestry Concession (HPH) in 2002 (MoF, 2002) as coloured polygons.

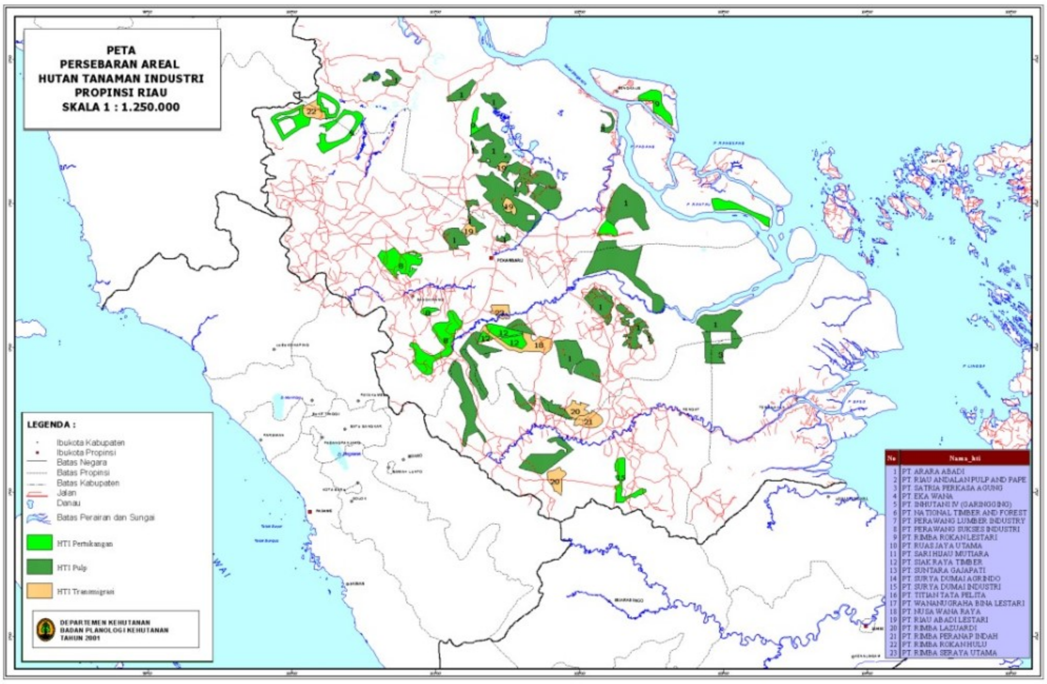


Figure 2.6 Map of Industrial Timber Plantation (HTI) in 2002 (MoF, 2002) as concession for furniture tree (light green), pulp (dark green) and transmigration (cream).

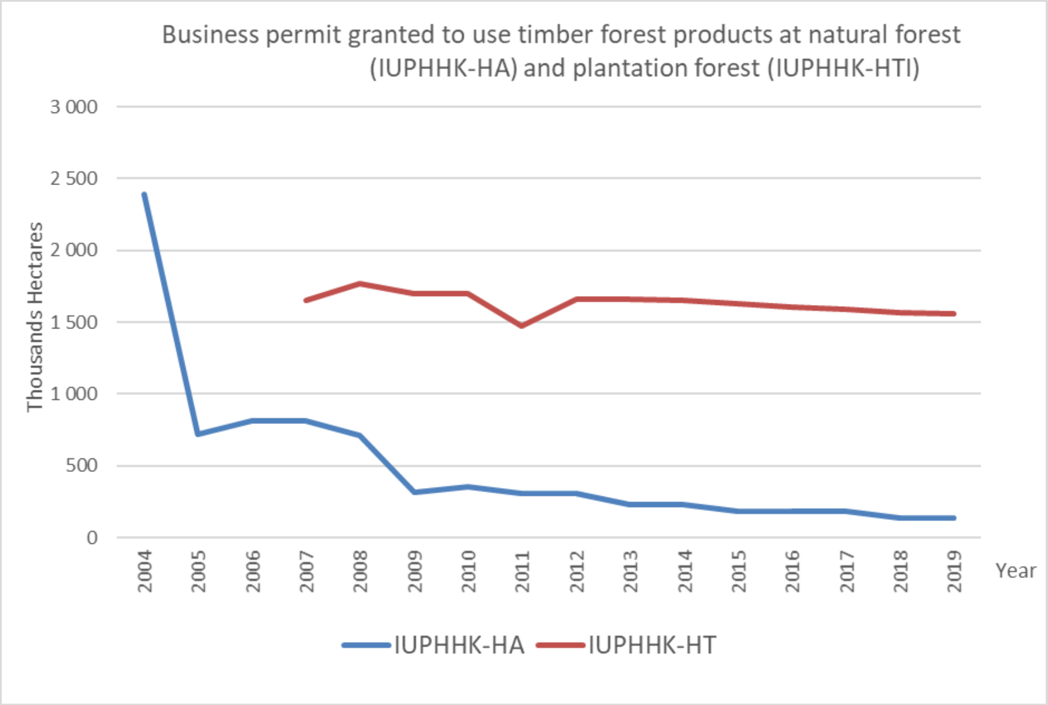


Figure 2.7 Business permit granted to use timber forest products at natural forest / IUPHHK-HA, (BPS, 2021) and plantation forest IUPHHK-HTI (compiled from Dishut Riau (2014),MoEF (2015) and MoEF (2020)).

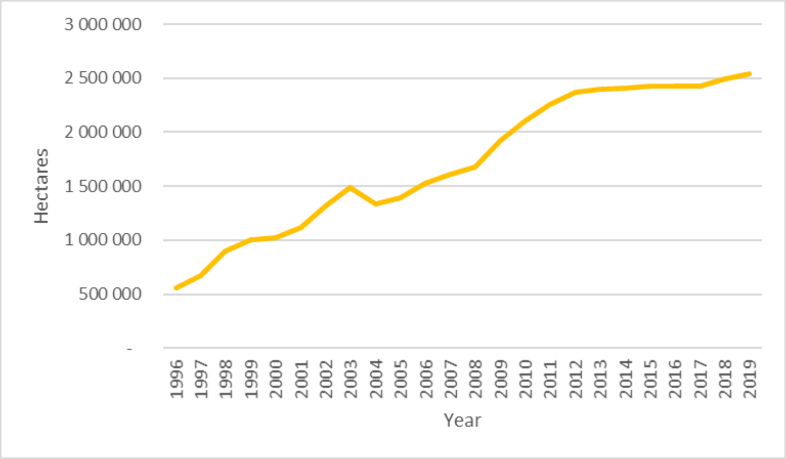


Figure 2.8 Oil palm expansion (in hectare) between 1996 and 2019. Figures before 2004 including Kepulauan Riau areas. (Compiled from books of "Riau in Figures" year 2000, 2006, 2011, 2016 and 2020). Kepulauan Riau is a cluster of islands off the coast Riau which in 2004 became a separate province.

2.1.4 Legal Situation

Indonesia has a complex set of rules and regulations concerning land-tenure, peatlands, forest, forest protection and forest fire. According to Article 7 of Regulation Number 12 Year 2011 , Indonesian law is following a hierarchy of legal forms :

1. The 1945 Constitution ("Undang-Undang Dasar 1945")
2. Decree of the People's Representative Assembly ("Ketetapan MPR")
3. Law ("Undang-Undang") , or government regulation in lieu of law ("Peraturan Pemerintah Pengganti Undang-Undang")
4. Government regulation ("Peraturan Pemerintah")
5. Presidential decree ("Peraturan Presiden")
6. Provincial regulation ("Peraturan Daerah Provinsi")
7. Regency or municipality regulation ("Peraturan Daerah Kabupaten / Kota")

Indonesia constitution in the Article 33 (3) stated that "The land and the waters as well as the natural riches therein are to be controlled by the state to be exploited to the greatest benefit of the people". Furthermore, Regulations Number 4 Year 1982 assigns the principle of natural development as "Environmental management is based on the preservation of a harmonious and balanced environmental capacity to support sustainable development for the improvement of human welfare". Forest fire is related to law in the following aspects:

a Land tenure

Based on Regulation No 5 Year 1967 in Basic Forestry Law, Indonesia forest estate (“kawasan hutan”) is defined as “a forested or non-forested area that has been designated as a forest (Article 4)” and Article 2(a) defines state forest (“hutan negara”) as a forest estate and the forest growing on land that are not encumbered with ownership rights (“hak milik”). Following that regulation, Government Regulation Number 21 Year 1970 allowed companies to exploit forest by Commercial Forestry Concessions (Hak Pengusahaan Hutan - HPH) and local people to harvest forest products by Forest Product Harvest Concession (Hak Pemungutan Hasil Hutan – HPHH) as long as they did not disturb the operation of business concessions. Later, Government Regulation (PP) No.21/1970 jo PP. No.18/1975 facilitate foreign investment into forestry industry since HPH must be in the form of “limited liability company (Perseroan Terbatas)”. To meet the needs of raw materials for the forest product industry, the government opened the licensing of Industrial Timber Plantation (HTI – Hutan Tanaman Industri) which is a production forest (HP-Hutan Produksi) by applying intensive silviculture (Government Regulation PP No. 7 Year 1990 Industrial Timber Plantation), this allowed clear cutting followed by replanting (Article 4) for a period of 35 years plus the cycle of the main crop being cultivated (Article 8).

Regulation Number 41 Year 1999 on Forestry divides forests based on their main functions as conservation forest (“hutan konservasi”), protected forest (“hutan lindung”), and production forest (“hutan produksi”). This regulation also mentions “Hutan Adat – customary forest / indigenous forest” is a form of “Hutan Negara – state forest” which is within the territory of the customary law community (Article 1 point 6, Article 5 point 2). Constitutional Court Decision Number 35/PUU-X/2012 granted judicial review on Regulation Number 41 Year 1999 which cancelled the government rights to take over the rights of the unity of indigenous people on customary forest areas. From at least 308 customary groups in Riau (Anggoro, 2020) only six are formalized.

b Peatland Management

According to Presidential Decree No 32 Year 1990 peat area is “peat soils with a thickness of 3 meters or more which is located upriver and swamps”. By that regulation, peat areas are considered as a protected area, so it is prohibited to carry out cultivation activities, except those which do not disturb the protection function. In 2002, Indonesia countersigned the ASEAN Agreement on Transboundary Haze Pollution (AATHP) which aims to prevent and monitor transboundary haze pollution as a result of land and/or forest fires. Indonesia was the last member state to adopt the agreement in 2014 by Law No. 26 year 2014 on the Adoption of AATHP (Syaufina, 2018).

In line with the AATHP, the Government of Indonesia has released policy on peatland management in Government Regulation No. 71 Year 2014 on Peat Ecosystem Protection and Management which was revised by the Government improved the Regulation by Government Regulation (PP) No. 57/2016 on Changing of the Government Regulation No. 71/2014 on Peat Ecosystem Protection and Management. One important thing in this law is Article 1 which includes the term of peatland hydrological unity (Kesatuan Hidrologis Gambut – KHG) which shall be a peat ecosystem located between two rivers, between a river and a sea, and /or at swamp (Figure 2.9). In addition, Article 9(3) of this regulation said “The Minister shall determine the protection function of the Peat Ecosystem of at least 30% (thirty percent) of the total area of the Peat Hydrological Unity and located at the peak of a Peat Dome and its surroundings”. The Regulation of the Minister of Environment and Forestry No 130 Year 2017 concerning Determination of the National Peat Ecosystem Function Map established 59 peatland hydrological unity (PHU) in Riau consisting of 2 637 704 hectares with protection function and 2 717 670 hectare with cultivation function, accounted for 55.76% of PHUs area in Sumatra.

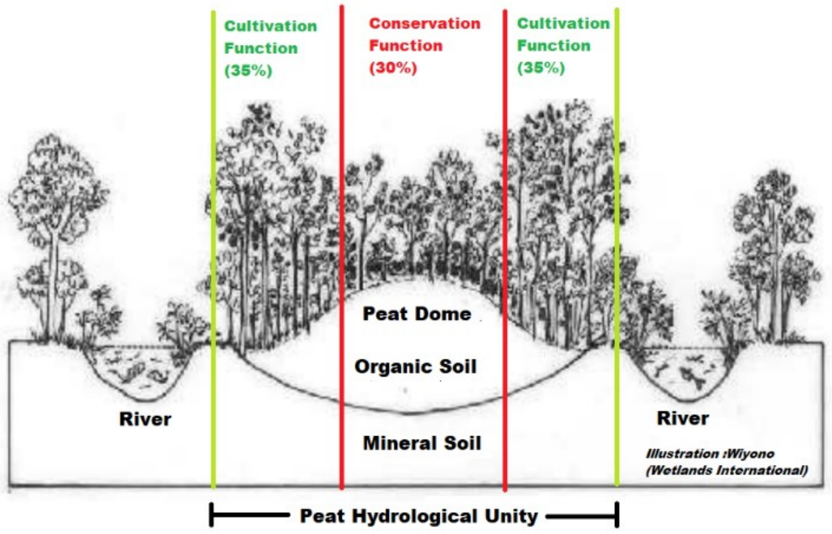


Figure 2.9 Peat Hydrological Unity.

To reduce deforestation and forest degradation, a moratorium on forest and peat permits has been declared in Presidential Instruction No 10 Year 2011 on Postponement of Granting New Licenses and Improvement of Natural Primary Forest and Peatland Governance and its renewals. The instruction suspends new licenses on primary natural forests and peatlands in conservation forests, protected forests, production forests and other use areas, except for :

- application that has received principle approval from the Minister of Forestry;
- implementation of vital national development, namely: geothermal, oil and gas, electricity, land for rice and sugar cane;
- extension of forest utilization permit and / or use of existing forest area as long as the permit of business is still valid
- ecosystem restoration.

Furthermore, the instruction is emphasized by the Presidential Instruction Number 5 of 2019 to be the termination of the issuance of new permit applies to the use of primary natural forest areas and peatlands, but with additional exceptions given such as:

- extension of forest utilization permit and/or use of existing forest area as long as the permit of business is still valid and meets the sustainability requirements;
- preparation of the central government/ capital city/ national, provincial or cities / municipalities government headquarters;
- infrastructure which is a national strategic project stipulated by Presidential Regulation as well as the improvement of existing infrastructures.

In order to accelerate the recovery and restoration of the hydrological function of peat damaged mainly by fire and drainage, the government of Indonesia has established the Peat Restoration Agency (Badan Restorasi Gambut BRG) by Presidential Decree No 1 Year 2016. BRG prioritize restoration of 2.49 million hectares or 19.26% of the total peatland areas in burn scar areas from the 2015 fire, peat dome with canals and shallow peatland for cultivation covering 332 776 hectares of conservation area, 1 410 926 hectares of concession area and 748 818 hectares of other areas (BRG, 2019). Until 2018, the agency has constructed 11 800 deep wells, 5 936 canal blockings, and 242 canal backfillings as rewetting infrastructures for 679 901 hectares area (BRG, 2019).

c Forest protection

In terms of forest protection, regulation PP No.28/1985 Article No 9 states “Everyone is prohibited from cutting down trees in the forest without permission from the authorized official”, while Article 10 states “Everyone is prohibited from burning forests except with legal authority”. Fires are also prohibited through the Decree of General Director of PHPA No. 248/Kpts/DJ-VI/1994 on Standard Procedure for Prevention and Management of Forest Fires. The zero burning policy is adopted in Government Regulation No 4/2001 on Control of Environmental Degradation and/or Pollution Related to Forest and/or Land Fires that every person is completely prohibited from conducting land/forest burning activities (Article 11). Moreover, Article 18, point 1 of that regulation states that “business owner must responsible for the occurrence of forest and / or land fires in the location of his business and must immediately take action to overcome forest and / or land fires in his business location”. For state forest areas, the Government Regulation No 45 Year 2004 on Forest Protection applies which says “protection of forest in a forest management unit (Kesatuan Pengelolaan Hutan Konservasi - KPHK), a protected forest management unit (Kesatuan Pengelolaan Hutan Lindung - KPHL), and a production forest management unit (Kesatuan Pengelolaan Hutan Produksi KPHP) is under the authority of government and/or regional government” (Article 2 and 3).

The explanation section of Article 1 of regulation No 24 Year 2007 on Disaster Management mentioned forest / land fires both caused by humans (non-natural disaster) and due to natural facto (natural disaster). Article 69 point (1.h) of Regulation No 32/2009 on Environmental Protection and Management included a stronger statement as “Everyone is prohibited clearing land by burning”. Later, the subject of regulation was updated by Regulation No 18 Year 2013 on Prevention and Eradication of Forest Destruction. “Everyone is an individual and / or corporation that does forest destruction organized in the jurisdiction of Indonesia and / or have legal consequences in the jurisdiction of Indonesia (Pasal 21)”. Regulation No 39 Year 2014 on Plantations (Article 67 point 3) requires plantation companies to make a statement ability to provide facilities, infrastructure, and emergency response systems that are adequate to cope with fires. Recently, Presidential Instruction Number 3 of 2020 called for intensified efforts of mitigation and ordered upholding law enforcement against forest and land fires crimes.

Table 2.2 summarizes that the current institutional and regulatory frameworks are still very much focused on emergency response (Nurhidayah and Djalante, 2017).

Table 2.2 Regulatory framework to land and forest risk management in Indonesia. Type of fires are land fires (LF) and forest fires (FF). Regulatory framework : preventions and mitigation (PM), emergency and response (ER), and recovery and rehabilitation phase (RR). Modified from: (Nurhidayah and Djalante, 2017).

Legislation	Issues specific to Fire	Type of Fire	Regulatory Framework
Law No. 32/2009 on Environmental Protection and Management	Main legislation/umbrella legislation on environment protection in Indonesia Article 69 (h) it is prohibited to open the land with burning	LF	PM
Law No. 41/1999 on Forestry	Main legislation on forest management in Indonesia Article 50 (3) (d) (l) Prohibition burning forest	FF	PM
	Article 78 (3) Criminal sanction, imprisonment for 15 years and IDR 5 billion fine		
Law No. 39/2014 on Plantation	Main legislation on the management of plantations including permits for oil palm plantations Article 67 (3) (c) statement of company to provide equipment and facility for emergency response to control land/forest	LF, FF	ER
Law No. 24/2007 on Disaster Management	Main legislation on disaster management system in Indonesia. No provision specific to forest fires		PM, ER, RR
Government Regulation No. 4/2001 Concerning	Articles 11,12,13, 14, 15, 16 prohibition and prevention on land/forest burning	LF, FF	PM

Control of Environmental Degradation and/or Pollution Related to Forest and/or Land Fires	Articles 17, 18,19 forest fires control/repression	FF	PM
	Article 20, 21 forest fires rehabilitation	FF	RR
	Article 23 -33 institutional framework in controlling land/forest fires at national, provincial and regional level	LF, FF	PM
	Articles 34-41 Monitoring and Reporting		PM
	Article 42 Community Awareness		
	Articles 43- 46 The role of community		PM, ER
	Article 52 Criminal Sanction Specific sub-legislation addressing land/forest fires		
Government Regulation No. 45/2004 on Forest Protection	Article 18-31 on prevention, repression and post-fire management. Regulation on forest protection from deforestation and forest degradation	FF	PM, RR
Presidential Instruction No. 16/2011 on Improvement in Controlling Land/Forest Fires	The first part is a general mandate, obligating 15 government institutions at the central and local government levels: To improve land/forest fire control through several activities: Prevention of land/forest fires; Fire fighting; Post-fire rehabilitation;	LF, FF	PM, RR
	To cooperate and coordinate in controlling land/forest fires;	LF, FF	PM, ER

	To improve community involvement and the involvement of other stakeholders in controlling land/forest fires;	LF, FF	PM
	To improve law enforcement and apply strict sanctions to individuals or corporations involved in burning land/forest fires.	LF, FF	PM
	The second part contains a specific mandate to each government institution listed in the regulation. Regulation on improving the efforts in controlling land/forest fires		PM, ER

2.2 Dataset

Data used in this research include administrative boundary, fire hotspots, land use, land cover and land type. Data processing was mostly conducted using R packages.

2.2.1 Administrative Boundary

The administrative boundary for Riau was obtained from (http://www.gadm.org/) though raster::getData command. The highest level is provincial perimeter of Riau, then Level-2 is district (kabupaten).

2.2.2 Fire Hotspot Dataset

The Government of Indonesia adopts hotspots as “the indicators of a location that has a relatively high temperature compared to surrounding temperatures” (The Ministry of Forestry Regulation No. P12/Menhut-II/2009 on the Control of Forest Fires). This research uses the MCD14ML Global Monthly Fire Location Product Collection 6, which contains the geographic coordinates of individual active fire hotspots. Hotspot pixels are detected by the Moderate Resolution Imaging Spectroradiometer (MODIS) instrument on Terra and Aqua satellites. The Terra satellite passes the same region of

Earth every 1–2 days at approximately 10:30 A.M. local time, while Aqua overpasses at 1:30 P.M. local time (Table 2.3). The restricted satellite overpass time may result in missed fire detections due to cloud cover or fire occurring when the satellites are not overhead. For example, morning or evening fires will remain undetected.

Table 2.3 MODIS Technical Specifications (NASA LAADS DAAC, 2020)

Orbit:	705 km, 10:30am descending node (Terra) or 1:30p.m. ascending node (Aqua), sun-synchronous, near-polar, circular
Repeat Cycle:	16 days
Swath Dimensions:	2330 km (cross track) by 10 km (along track at nadir)
Field of View:	110 degree
Wavebands:	36 bands: 1-19 from 405 to 2155nm 20-36 from 3.66 to 14.28 microns
Spatial Resolution:	250m (bands 1-2), 500m (bands 3-7), 1000m (bands 8-36)
Quantization:	12 bits

All objects with a temperature above absolute zero (0 K) emit energy in the form of electromagnetic radiation. Figure 2.10 shows the spectral radiance curve for a flame, a smoldering fire and the ambient background. The MODIS instrument has 36 bands (Figure 2.11) with three spatial resolutions: 250 m (bands 1–2), 500 m (bands 3–7), 1000 m (bands 8–36). Table 2.4 shows the channels used for active fire detection in MODIS Collection 6. MODIS's fire detection algorithm was inherited from previous algorithms on AVHRR and VIRS systems (Kaufman et al., 1998) which exploit the middle and far infrared wavelength transmittance characteristics in the atmosphere (Figure 2.12).

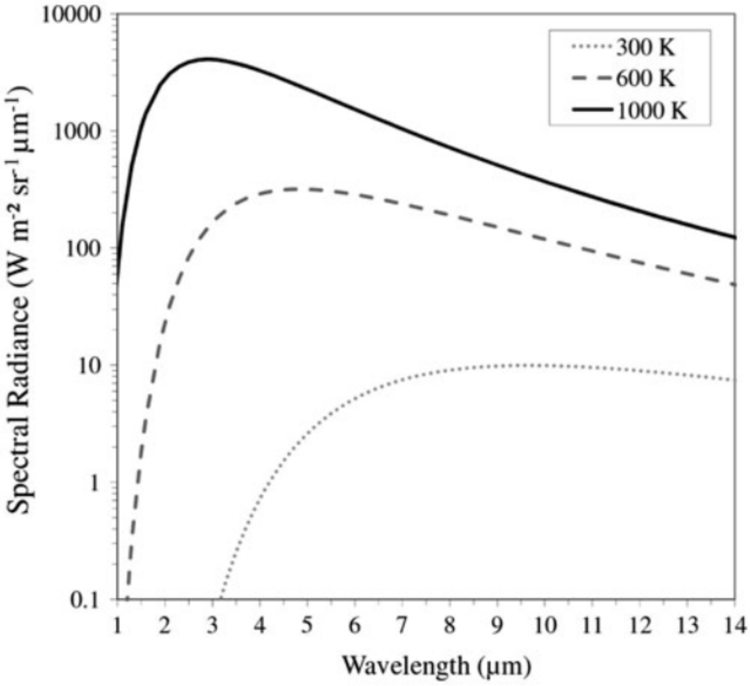


Figure 2.10 Modelled thermal emission for a flame (1000 K), a smoldering fire (600 K) and the ambient background (300 K). Calculations were made using Planck's Law assuming blackbody behaviour (Wooster et al., 2013).

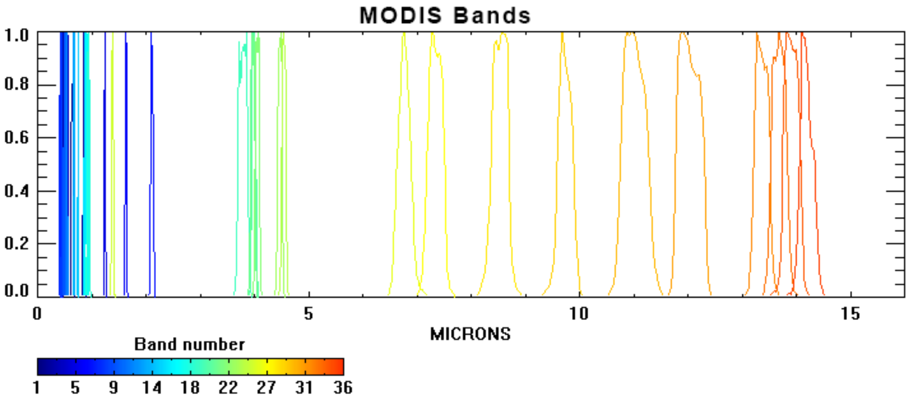


Figure 2.11 MODIS Bands (H S U, 2016).

Table 2.4 Channels to determine active fire in MODIS Collection 6 (Giglio et al., 2016; NASA LAADS DAAC, 2020).

Band Number	Purpose	Bandwidth (µm)	Spectral radiance (W/m^2 -µm-sr)
1	Sun glint and coastal false alarm rejection; cloud masking.	0.620 – 0.670	21.8
2	Bright surface, sun glint, and coastal false alarm rejection; cloud masking.	0.841 – 0.876	24.7
7	Sun glint and coastal false alarm rejection.	2.105 – 2.155	1.0
21	High-range channel for active fire detection.	3.929 - 3.989 [T_4]	2.38 (335K)
22	Low-range channel for active fire detection.	3.929 - 3.989 [T_4]	0.67 (300K)
31	Active fire detection, cloud masking, forest clearing rejection.	10.780 - 11. 280 [T_{11}]	9.55 (300K)
32	Cloud masking.	11.770 - 12.270	8.94 (300K)

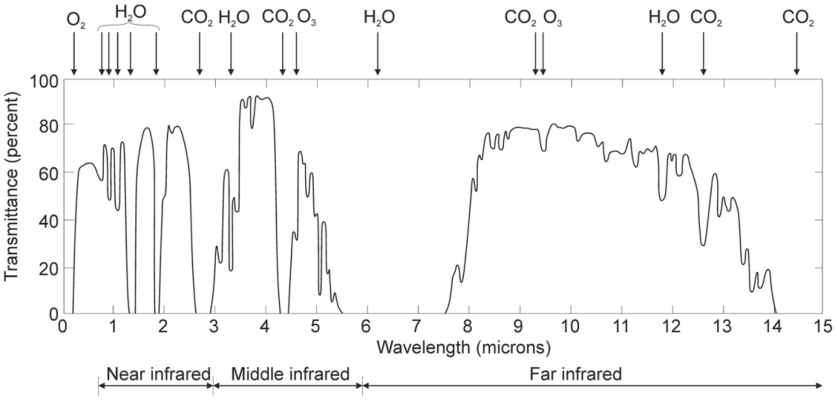
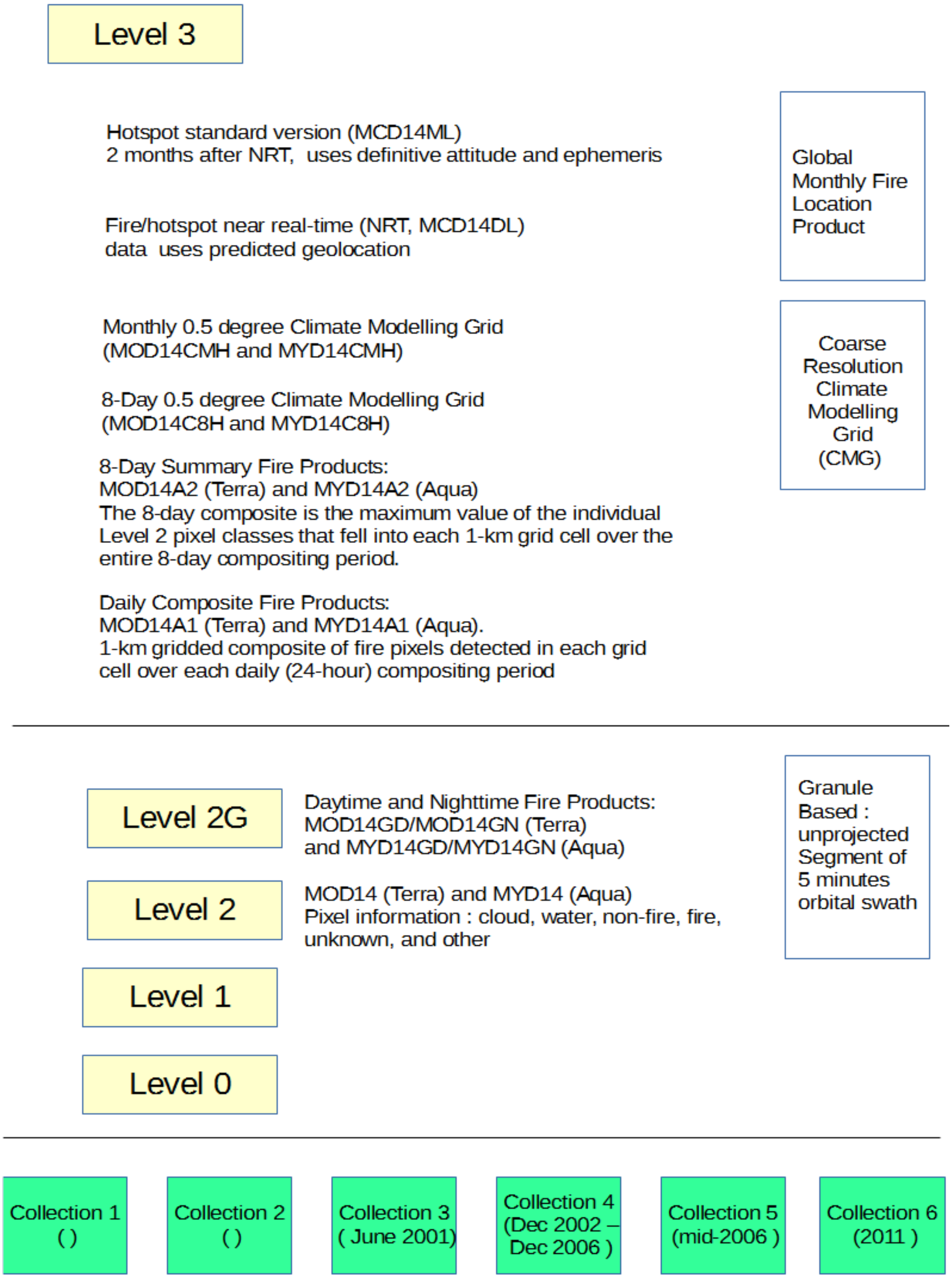


Figure 2.12 Transmittance through the atmosphere as function of wavelength (Mikolajczyk et al., 2017).

Justice et al. (2002a) describes that in the initial MODIS fire product, the absolute fire must satisfy at least one of two conditions:

1. T_4 > 360 K (330 K at night)
2. T_4 > 330 K (315 K at night) and T_4-T_{11} > 25 K (10 K at night)

While detection of weaker fires (daytime T_4 > 310K or night-time T_4 > 305 K, and T_4-T_{11} >10 K) involves the relative thermal emission of surrounding pixels. MODIS Collection 6 products are processed using the improvement of this algorithm with several contextual tests such as non-fire background checking, false alarm elimination caused by sun glint, hot desert surface, and coasts or shorelines (Giglio et al., 2003). Figure 2.13 shows the hierarchy of MODIS fire products (Giglio, 2010).



Hotspot standard version (MCD14ML)
2 months after NRT, uses definitive attitude and ephemeris

Fire/hotspot near real-time (NRT, MCD14DL)
data uses predicted geolocation

Monthly 0.5 degree Climate Modelling Grid
(MOD14CMH and MYD14CMH)

8-Day 0.5 degree Climate Modelling Grid
(MOD14C8H and MYD14C8H)

8-Day Summary Fire Products:
MOD14A2 (Terra) and MYD14A2 (Aqua)
The 8-day composite is the maximum value of the individual Level 2 pixel classes that fell into each 1-km grid cell over the entire 8-day compositing period.

Daily Composite Fire Products:
MOD14A1 (Terra) and MYD14A1 (Aqua).
1-km gridded composite of fire pixels detected in each grid cell over each daily (24-hour) compositing period

Daytime and Nighttime Fire Products:
MOD14GD/MOD14GN (Terra)
and MYD14GD/MYD14GN (Aqua)

MOD14 (Terra) and MYD14 (Aqua)
Pixel information : cloud, water, non-fire, fire, unknown, and other

Figure 2.13 MODIS fire products.

The hotspot dataset is downloaded from https://firms.modaps.eosdis.nasa.gov/download/ and then subsequent analysis completed using R. In addition to fire hotspot location, other MCD14ML attributes include acquisition time, confidence level, and fire radiative power (FRP). The ranges for confidence class of fire pixel are low (0–30), nominal (30–80), or high (80–100) (Giglio, 2010). Previous work found a high commission error in areas of low fire activity (Hantson et al., 2013), so we restrict our analysis to high confidence hotspots. Figure 2.14 shows total number of high confidence fire hotspots detected between 2001 and 2012.

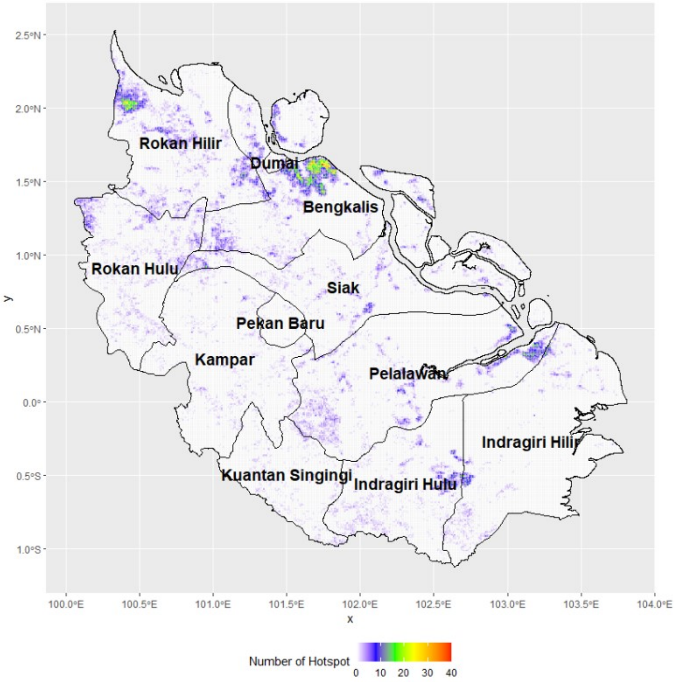


Figure 2.14 Total number of high confidence fire hotspots detected between 2001 and 2012.

2.2.3 Tree Cover Dataset

For information on tree cover loss we use the Global Forest Change (GFC) dataset (Hansen et al., 2013) derived from band 3, 4, 5, and 7 of Landsat 7 Enhanced Thematic Mapper Plus (ETM+) images, with 30 m resolution. The satellite orbiting the Earth at 705 km altitude, imaging the entire globe every 16 days and each scene has 183 km wide swath by 170 km long (NASA). Table 2.5 shows the characteristics of Landsat bands user for forest change monitoring.

Table 2.5 Landsat Bands Used for Global Forest Change (NASA).

Landsat Band	Wavelength (μm, 1×10^{-6} m)	Scale Factor	Description of Use
Band 3 (red)	0.63 – 0.69	508	Vegetation type identification; soils and urban features
Band 4 (Near Infrared)	0.74 – 0.90	254	Vegetation detection and analysis; shoreline mapping and biomass content
Band 5 (Shortwave Infrared-1)	1.55 – 1.75	363	Vegetation moisture content/drought analysis; burned and fire-affected areas; detection of active fires
Band 7 (Shortwave Infrared-2)	2.09 – 2.35	423	Additional detection of active fires (especially at night); plant moisture/drought analysis

We use the Hansen_GFC-2017-v1.5 dataset, which contains information on tree canopy cover for year 2000 (treecover2000) and year of gross forest cover loss over the period 2000–2017 (lossyear). Tree cover loss over 2000 to 2017 period has not been produced in a consistent way, so we restrict our analysis to 2000 to 2012, when a consistent analysis of forest loss is available. Figure 2.15 shows the fractional tree cover loss between 2001 and 2012.

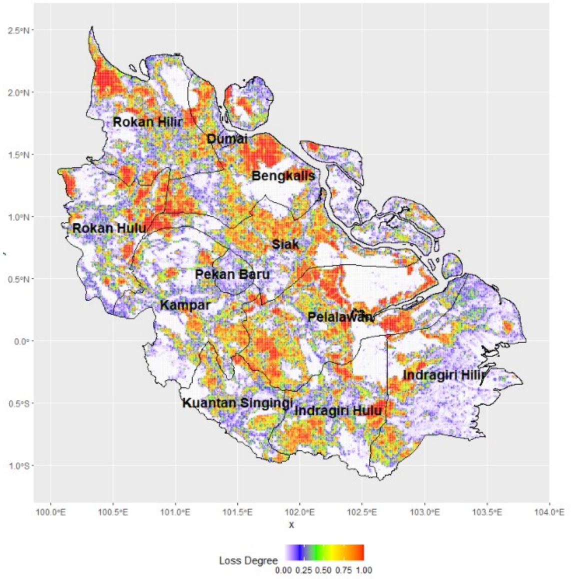


Figure 2.15 Fractional tree cover loss between 2001 and 2012.

GFC defines trees as all vegetation taller than 5 m in height. Forest loss occurs when tree cover declines to < 50%, and includes loss of forest as a result of fire. Forest loss includes clearance of plantations and oil palm estates as well as loss of natural forest. Forest cover loss is determined using a decision tree on reflectance values, mean reflectance and slope of linear regression of band reflectance value versus image date. Forest loss as a stand-replacement disturbance, or a change from a forest to non-forest state is encoded as 1 in this dataset. In addition, the Loss Year dataset represents the disaggregation of total forest loss to annual time scales. It is encoded as a value in the range 1-12 - representing loss detected primarily at respective year (2001-2012), while 0 indicated no loss.

The GFC provides 10x10 degree tiles, consisting of seven files per tile. All files contain unsigned 8-bit values and have a spatial resolution of 1 arc-second per pixel, or approximately 30 meters per pixel at the equator. The dataset contains :

- Tree canopy cover for year 2000 (treecover2000)
- Global forest cover loss 2000–2014 (loss)
- Global forest cover gain 2000–2012 (gain)
- Year of gross forest cover loss event (lossyear)
- Data mask (datamask)
- Circa year 2000 Landsat 7 cloud-free image composite (first)
- Circa year 2014 Landsat cloud-free image composite (last).

Data is available on-line from: https://earthenginepartners.appspot.com/science-2013-global-forest/download_v1.5.html. Files downloaded for Riau Province coverage are:

- Hansen_GFC-2017-v1.5_treecover2000_00N_100E.tif
- Hansen_GFC-2017-v1.5_gain_00N_100E.tif
- Hansen_GFC-2017-v1.5_lossyear_00N_100E.tif
- Hansen_GFC-2017-v1.5_datamask_00N_100E.tif
- Hansen_GFC-2017-v1.5_first_00N_100E.tif
- Hansen_GFC-2017-v1.5_last_00N_100E.tif
- Hansen_GFC-2017-v1.5_treecover2000_10N_100E.tif
- Hansen_GFC-2017-v1.5_gain_10N_100E.tif
- Hansen_GFC-2017-v1.5_lossyear_10N_100E.tif
- Hansen_GFC-2017-v1.5_datamask_10N_100E.tif
- Hansen_GFC-2017-v1.5_first_10N_100E.tif
- Hansen_GFC-2017-v1.5_last_10N_100E.tif

2.2.4 Land Cover Dataset

We used the land-cover map provided by the Indonesian Ministry of Environment and Forestry which is available at http://webgis.menlhk.go.id:8080/pl/pl.htm (Margono et al., 2016). The map includes land-cover classifications for 1990, 1996, 2000, 2003, 2006 and 2009, then annually between 2011 and 2017. Before 2000, the land-cover classification was conducted as a part of National Forest Inventory (NFI) project which predominantly relied on analysis of Landsat imagery. During 2000–2009, digital Landsat images were combined with 1000 m SPOT Vegetation and 250 m MODIS images, but the classification still depended on visual image interpretation. Finally, since 2009 only Landsat images have been used as main data source and Landsat 8 OLI have been used since 2013. The land-cover dataset includes 31,785 polygons, with land-cover divided into 23 different land-cover classifications (Table 2.6) which we use to form nine grouped land-cover classes (Table 2.7).

Table 2.6 Land Cover Classes (Margono et al., 2016).

Class	Code	Description
Primary dryland forest	2001 (Hp)	Natural tropical forests grow on non-wet habitat including lowland, upland, and montane forests with no signs of logging activities. The forest is including pygmies and heath forest and forest on ultramafic and lime-stone, as well as coniferous, deciduous and mist or cloud forest.
Secondary dryland forest	2002 (Hs)	Natural tropical forest grow on non-wet habitat including lowland, upland, and montane forests that exhibit signs of logging activities indicated by patterns and spotting of logging. The forest is including pygmies and heath forest and forest on ultramafic and lime-stone, as well as coniferous, deciduous and mist or cloud forest.
Primary swamp forest	2005 (Hrp)	Natural tropical forest grow on wet habitat including brackish swamp, sago and peat swamp, with no signs of logging activities.
Secondary swamp forest	20051 (Hrs)	Natural tropical forest grow on wet habitat including brackish swamp, sago and peat

		swamp that exhibit signs of logging activities indicated by patterns and spotting of logging.
Primary mangrove forest	2004 (Hmp)	Inundated forest with access to sea/brackish water and dominated by species of mangrove and Nipa (*Nipa frutescens*) that has no signs of logging activities.
Secondary mangrove forest	20041 (Hms)	Inundated forest with access to sea/brackish water and dominated by species of mangrove and Nipa (*Nipa frutescens*) that exhibit signs of logging activities indicated by patterns and spotting of logging.
Plantation forest	2006 (Ht)	Planted forest including areas of reforestation, industrial plantation forest and community plantation forest.
Non-Forest Dry shrub	2007 (B)	Highly degraded log over areas on non-wet habitat that are ongoing process of succession but not yet reach stable forest ecosystem, having natural scattered trees or shrubs.
Wet shrub/ swampy shrub	20071 (Br)	Highly degraded log over areas on wet habitat that are ongoing process of succession but not yet reach stable forest ecosystem, having natural scattered trees or shrubs.
Savanna and Grasses	3000 (S)	Areas with grasses and scattered natural trees and shrubs. This is typical of natural ecosystem and appearance on Sulawesi Tenggara, Nusa Tenggara Timur, and south part of Papua island. This type of cover could be on wet or non-wet habitat.
Dry Agriculture	20091 (Pt)	All land covers associated to agriculture activities on dry/non-wet land, such as moor (*tegalan*), mixed garden and agriculture fields (*ladang*)
Mixed dry agriculture	20092 (Pc)	All land covers associated to agriculture activities on dry/non-wet land that mixed with shrubs, thickets, and log over forest. Tis cover

		type often results of shifting cultivation and its rotation, including on karts
Estate crop	2010 (Pk)	Estate areas that has been planted, mostly with perennials crops or other agriculture trees commodities
Paddy field	20093 (Sw)	Agriculture areas on wet habitat, especially for paddy, that typically exhibit dyke patterns (*pola pematang*).This cover type includes rainfed, seasonal paddy field, and irrigated paddy fields
Transmigration areas	20122 (Tr)	Kind of unique settlement areas that exhibit association of houses and agroforestry and/or garden at surrounding
Fish pond/ aquaculture	20094 (Tm)	Areas exhibit aquaculture activities including fish ponds, shrimp ponds or salt ponds
Bare ground/ Bare soil	2014 (T)	Bare grounds and areas with no vegetation cover yet, including open exposure areas, craters, sandbanks, sediments, and areas post fire that has not yet exhibit regrowth
Mining areas	20141 (Tb)	Mining areas exhibit open mining activities such as open-pit mining including tailing ground
Settlement areas	2012 (Pm)	Settlement areas including rural, urban, industrial and other settlements with typical appearance
Port and harbor	20121 (Bdr/ Plb)	Sighting of port and harbor that big enough to independently delineated as independent object
Open water	5001 (A)	Sighting of open water including ocean, rivers, lakes, and ponds
Open swamp	50011 (Rw)	Sighting of open swamp with few vegetation
Clouds and no-data	2500 (Aw)	Sighting of clouds and clouds shadow with size more than 4 cm^2 at 100.000 scales display.

Table 2.7 Land-cover classes, showing how we grouped land-cover types from Ministry of Environment and Forestry.

Grouped Land-Cover	Code	Original Land-Cover Types and Code
Primary dryland forest	PDF	Primary dryland forest (2001)
Primary peat swamp forest	PSF	Primary swamp forest (2005), Primary mangrove forest (2004)
Secondary dryland forest	SDF	Secondary dryland forest (2002)
Secondary peat swamp forest	SSF	Secondary swamp forest (20051), Secondary mangrove forest (20041)
Plantation	PLT	Plantation forest (2006), Estate crop (2010)
Shrub	SRB	Non-Forest Dry shrub (2007), Wet shrub/swampy shrub (20071), Savanna and Grasses (3000), Bareground/Bare soil (2014)
Water	WTR	Fish pond/aquaculture (20094), Open water (5001), Open swamp (50011)
Agriculture	AGR	Dry Agriculture (20091), Mixed dry agriculture (20092), Paddy Field (20093)
Urban	URB	Settlement areas (2012), Port and Harbor (20121), Transmigration Area (20122), Mining_Area (20141)

2.2.5 Land Use Dataset

Landuse datasets such as concession area, and protected area extents in 2010 are obtained from the World Resources Institute and accessed through Global Forest Watch (http://data.globalforestwatch.org/datasets). Concessions include oil palm, wood fiber, and logging concessions. Oil palm concessions are used for industrial-scale oil palm plantations. Wood fiber concessions are used for plantations of fast-growing tree species for wood pulp and paper production. Logging concessions are natural forest areas used for selective timber extraction (Marlier et al., 2015). Regions outside concessions and protected areas, are defined as “Other”. This “Other” land use is stated as a non-forest area (Area Penggunaan Lain / APL) by the Ministry of Forestry (Regulation No 50 Year 2009) whith examples such as agriculture, transmigration and mining (Suprapto et al., 2018).

2.2.6 Land Type Dataset

Land type dataset contain map of Peatland and Non-Peatland areas obtained from Global Forest Watch.

2.3 Data Processing

Most of the operations in this research are run in R software, involving sp or sf spatial objects. The later object is implemented using the common architecture for simple feature geometry formal standard and directly linked with GEOS geometry operations JST in C++, so usually it runs 30x faster than sp. There are three groups of operation applied in this section, namely preprocessing, combining and calculating derived attributes (Figure 2.16). During preprocessing, datasets are cleaned and selected based on time frame, spatial extent and attribute. Furthermore, land use and land cover data are combined using polygon overlay. Later, land use and land cover attributes are attached to hotspot points by spatial join. Finally, several attributes are calculated to support research objectives and algorithms used.

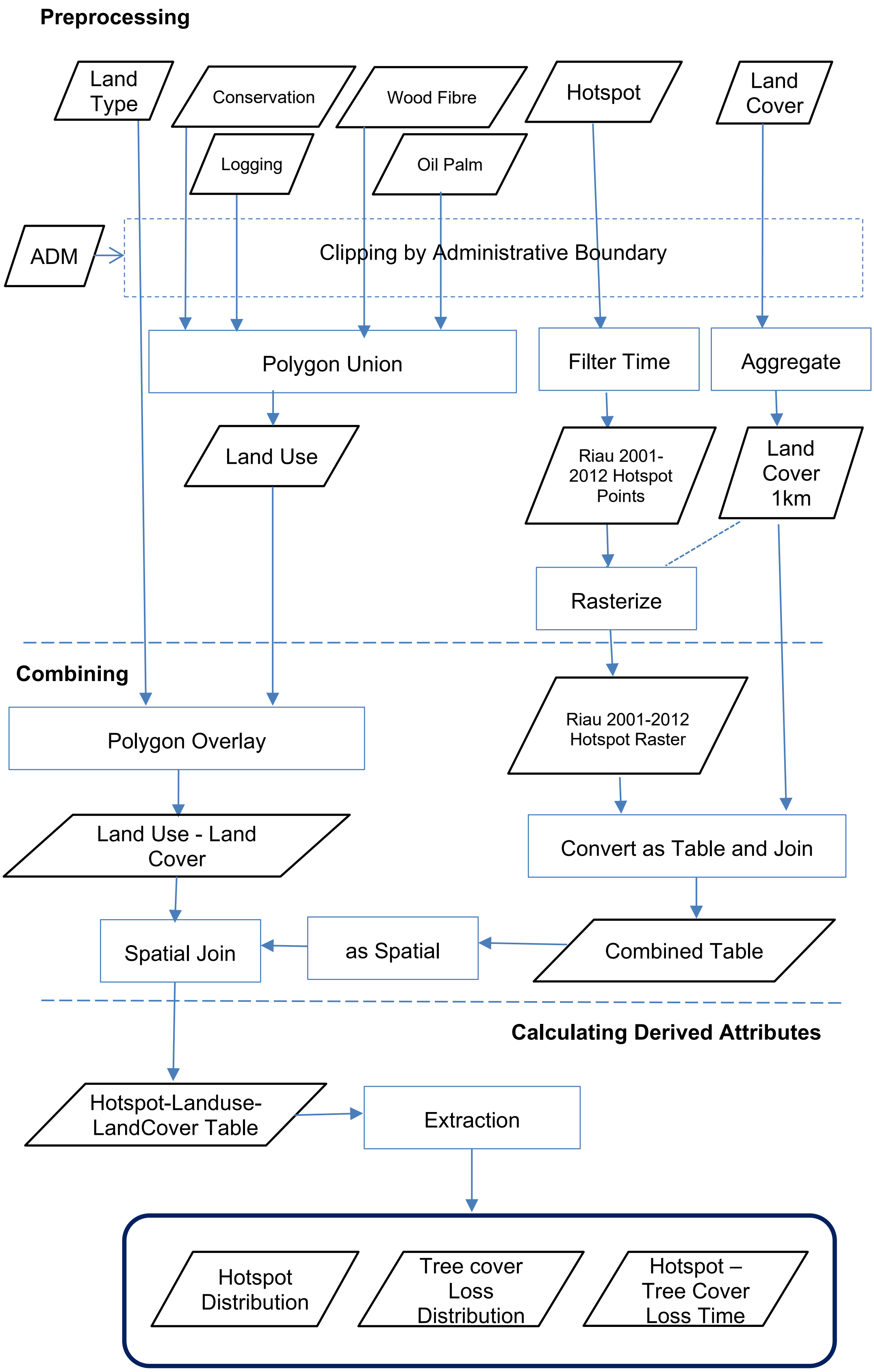


Figure 2.16 Basic Operations.

2.3.1 Preprocessing

In order to prepare the raw datasets for this research several procedures are applied for each data theme.

a Administrative Boundary

Riau Province is very large and lies on 4 Universal Transfer Mercator (UTM) Map Projection Zones namely 47N, 47S, 48N and 48S (Figure 2.17). Calculating distance and area across different zones will lead to some degree of bias. To avoid this issue we choose to work with all dataseta as WGS84 Geodetic Coordinate Reference System (EPSG: 4326). Conversion to sp/sf object class also required for further usage.

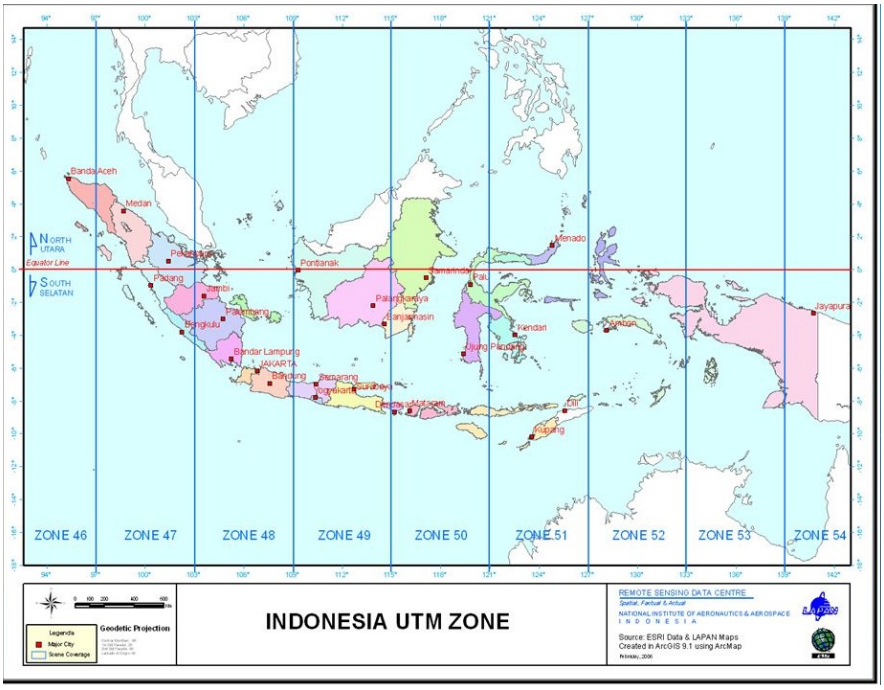


Figure 2.17 Indonesia UTM Zones.

b Fire Hotspot

The raw hotspot dataset from NASA FIRMS was loaded into the R environment as a spatial object using readOGR command from rgdal package. This function keeps the object's coordinate reference system information. Then, this is cropped by the Riau province boundary. Later, the district (kabupaten) label for each hotspot points are obtained. Furthermore, new columns are created to store district name, and date attributes. As the last steps of preprocessing phase, the number of hotspot points per 1 km^2 area is calculated. The Tree Cover Loss layer is converted as a raster.

c Land Use

Concession area datasets are provided at the national level and come with different attributes:

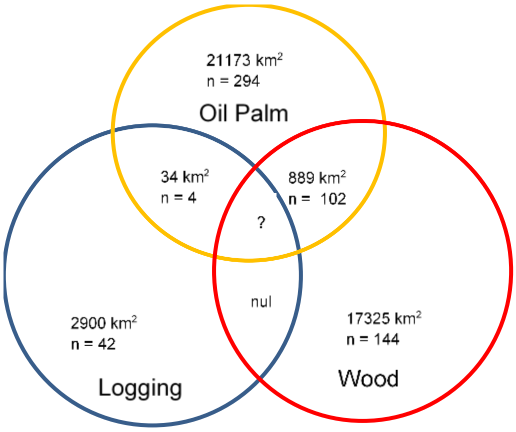
- Logging : name, permit_num, gfwid
- Fiber : group_comp, name, type, gfwid
- Oil palm : po_legalst, po_hgu, group_comp, type, name, gfwid

Each row in the dataset has gfwid valus as a Row identifier in the Global Forest Watch dataset. Then some attributes are selected and transformed if necessary to consolidate them (Table 2.8).

Table 2.8 Consolidated attributes of land use dataset.

Attribute	Logging	Wood Fiber	Oil Palm
Gfwid	Gfwid	gfwid	Gfwid
concession_type	“logging”	“wood_fiber”	“oil_palm”
name	Name	name	Name
Type	Na	type	Type
legal_status	permit_num	na	po_legalst
group_comp	Na	group_comp	group_comp

We remove the 1% of overlap areas among concession types (Figure 2.18), and classify the remaining regions as “other” land use type which relates to non-forest area (Figure 2.19).



Riau province area 89957 km2

Figure 2.18 Overlap Between Concession Areas.

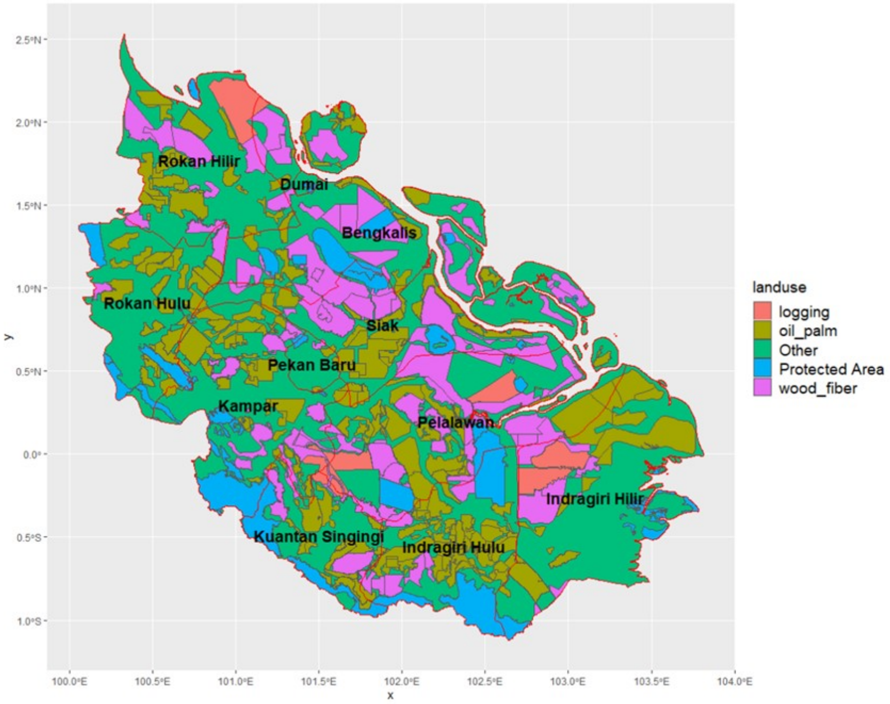


Figure 2.19 Consolidated Land use map.

d Land Type

The dataset related to land type contains information on peat distribution. So, regions outside that peat polygon are considered as non-peat. As a result, the land type map consists of peat and non-peat polygons (Figure 2.20).

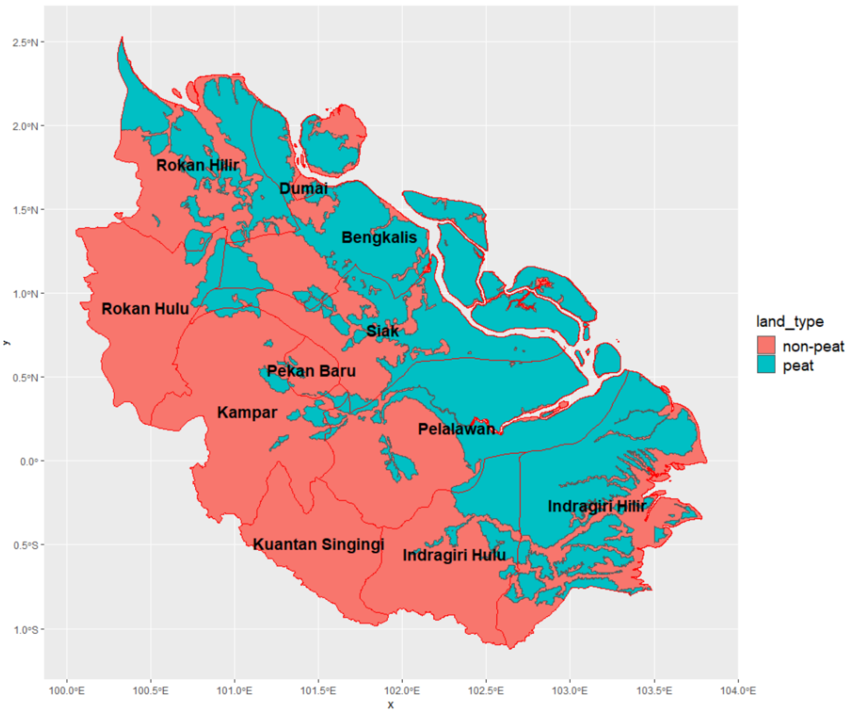


Figure 2.20 Land Type Map.

e Tree Cover

Tree cover condition involves several datasets, i.e. tree canopy cover (Figure 2.21) and tree cover loss. They are provided per grid area, and all were merged, cropped and masked. After the data was adjusted to the spatial extent of Riau Province, they are aggregated to a larger scale. The Tree Cover Loss layer (30 m) is aggregated to the 1 km scale using SUM function (Figure 2.22). The same process also applied to the Loss Year layer using MODAL function. In this dataset, tree cover loss is defined as a stand-replacement disturbance, or a change from a forest to non-forest state and encoded as 1 in this dataset.

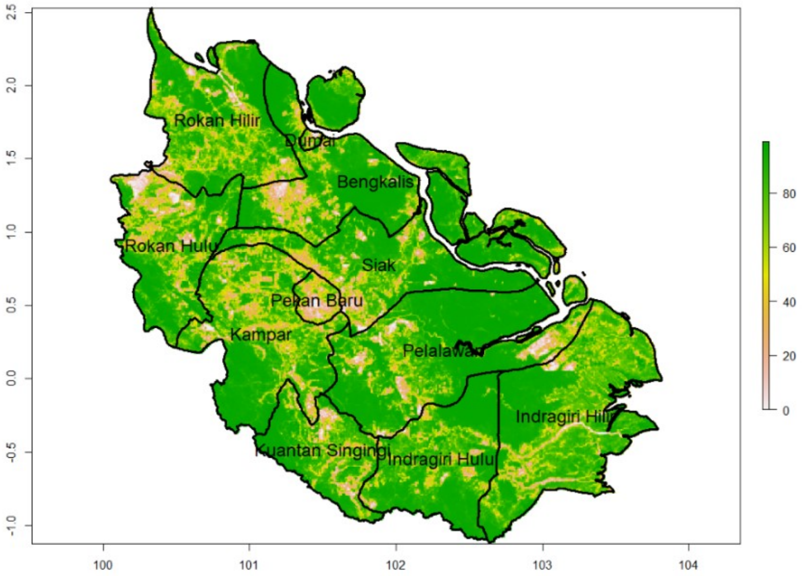


Figure 2.21 Percentage of Tree Canopy Cover in 2000.

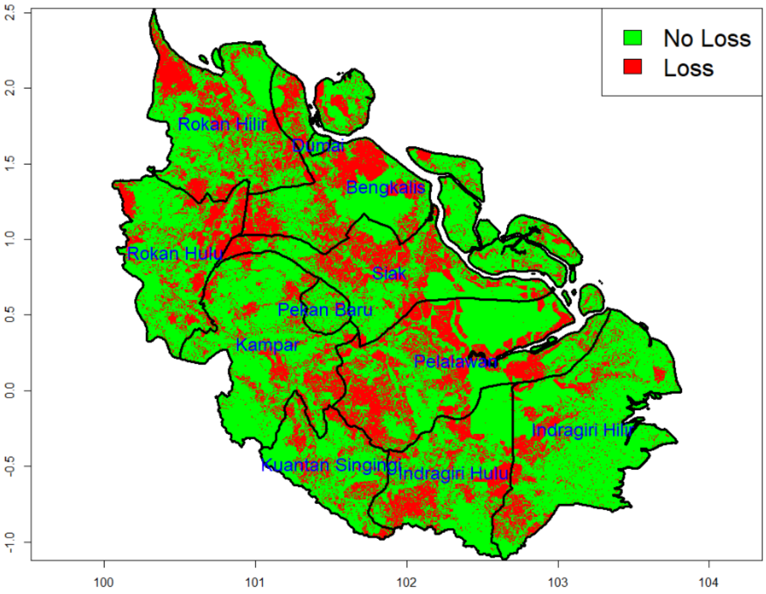


Figure 2.22 Tree Cover Loss Map.

The disaggregation of total loss to annual time scales is encoded as a value in the range 1-12 - representing loss detected primarily at the respective year (2001-2012). Because in that dataset 0 value indicates no loss, then it is altered into NA. Figure 2.23 shows tree cover loss every year between 2001 and 2012.

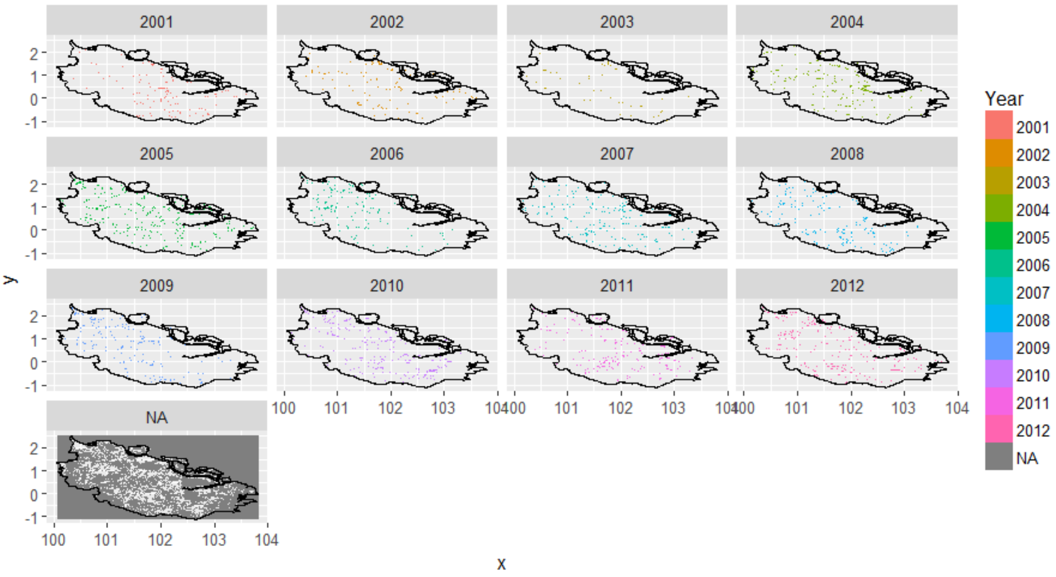


Figure 2.23 Annual Map of Tree Cover Loss (2001-2012).

2.3.2 Combining

The earlier preprocesing phase gives both raster and vector datasets. In this phase, raster datasets such as hotspot and tree cover are joined as a table. On the other hand, vector datasets i.e. land type and land use are joined using overlay function to produce polygons with attributes from both inputs. Next, results are combined using spatial join function (Figure 2.24).

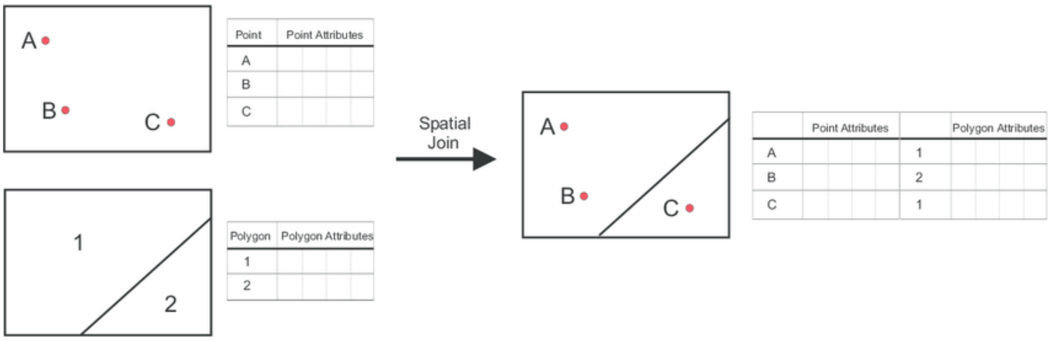


Figure 2.24 Point-Polygon Spatial Join (Davies and R. Davies, 2009).

2.3.3 Calculating Derived Attributes

After attributes from Hotspot, Landuse, Landcover and District are combined, some general attributes of the data are extracted (Table 2.9). Based on these general attributes then more columns are derived, such as:

- Hotspot Distribution (Figure 2.25)
- Tree cover Loss Distribution (Figure 2.26)
- Hotspot – Tree Cover Loss Time.

Table 2.9 Description of Combined Table Attributes.

Column	Type	Values	Descripton
xy	character	"100.328194444444 2.51069444510881"	Identifier Longitude and Latitude
losscount	numeric	0-64	number loss cell
lossyear	numeric	1-12	mode Loss year
hotspotcount	numeric	-	number of hotspot
district	factor		
landuse	factor	Logging, oil_palm, Other, Protected Area, wood_fiber	
land_type	factor	non-peat peat	
geometry	sfc_point		Point coordinate
x	numeric		longitude
y	numeric		latitude

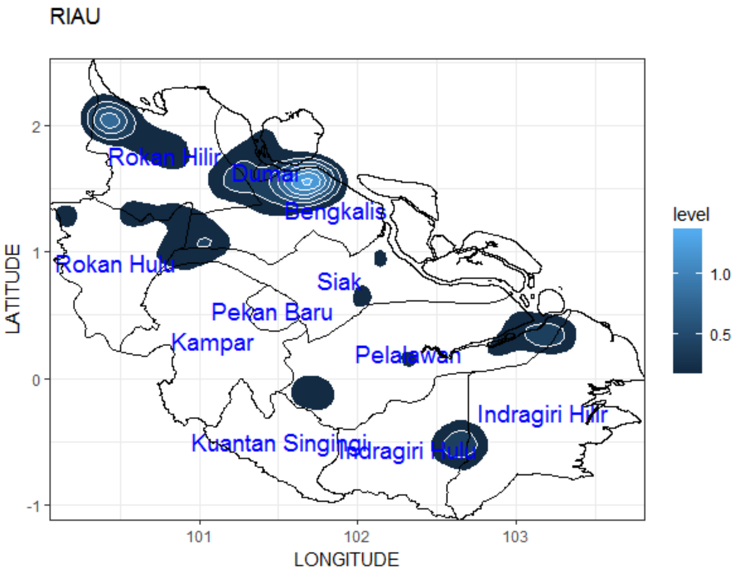


Figure 2.25 Hotspot Density Map.

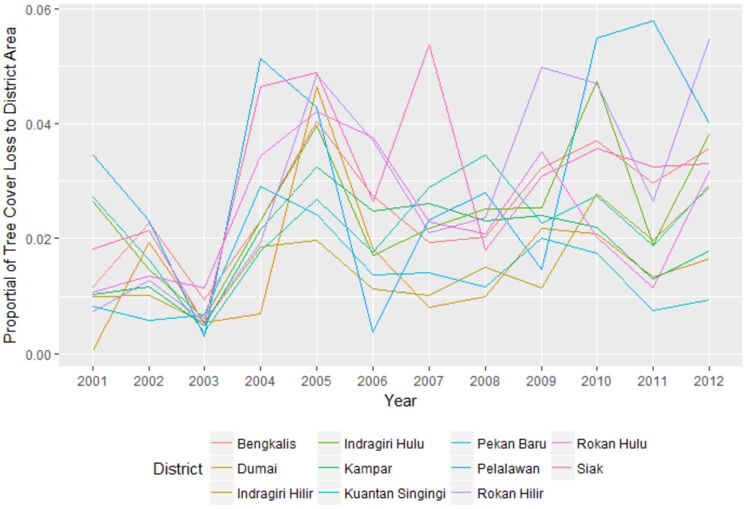


Figure 2.26 Proportion of Tree Cover Loss to District Area.

Hotspot – Tree Cover Loss Time

Briefly, hotspots points are split by year then converted into a raster. Later, the number of hotspot occurrences per year for each pixel were extracted. Then, the years with maximum hotspot events were calculated. In addition, the Loss Year attribute was derived by aggregating Tree Cover Loss Year using the modal function. In the same way, Loss Degree values were determined by transforming sum of loss. Then those three attributes were attached to the final table. Those steps are illustrated in Figure 2.27.

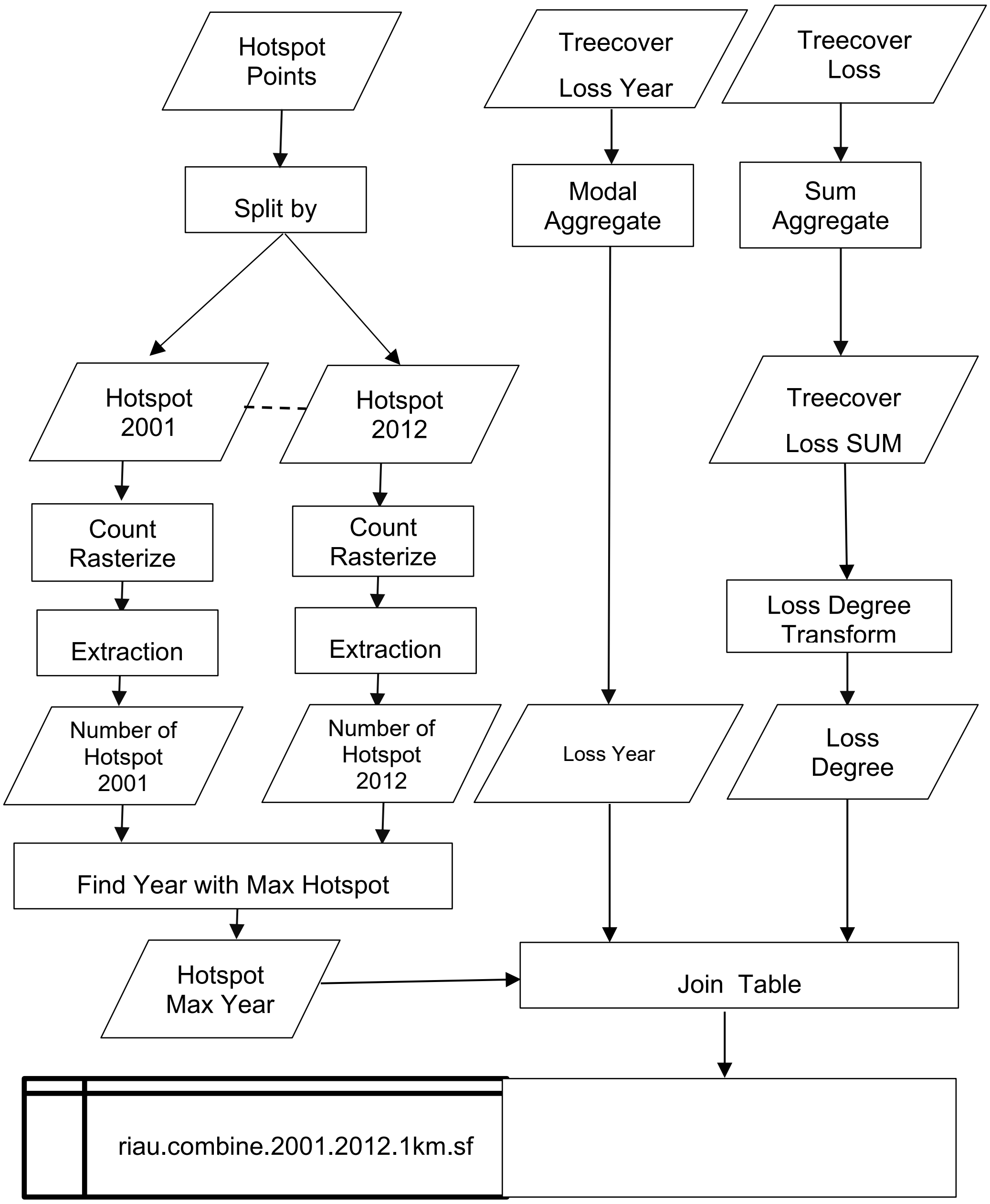


Figure 2.27 Calculation of Hotspot – Tree Cover Loss Time.

Bibliography

Adinugroho, W., Suryadiputra, N., Saharjo, B. and Siboro, L. 2005. *Manual for the Control of Fire in Peatlands and Peatland Forest.*

Albar, I. 2015. Typology Analysis of Land and Forest Fire in Riau Province, Indonesia. In: *International Workshop on Land Use/Cover Change and Air Pollution, 4-7 August 2015, Bogor*.

Aldrian, E. and Susanto, R.D. 2003. Identification of Three Dominant Rainfall Regions within Indonesia and Their Relationship to Sea Surface Temperature. *International Journal of Climatology.* **23**(12), pp.1435-1452.10.1002/joc.950

Amici, S., Wooster, M.J. and Piscini, A. 2011. Multi-Resolution Spectral Analysis of Wildfire Potassium Emission Signatures Using Laboratory, Airborne and Spaceborne Remote Sensing. *Remote Sensing of Environment.* **115**(8), pp.1811-1823.https://doi.org/10.1016/j.rse.2011.02.022

Andela, N., Morton, D.C., Giglio, L., Chen, Y., van der Werf, G.R., Kasibhatla, P.S., DeFries, R.S., Collatz, G.J., Hantson, S., Kloster, S., Bachelet, D., Forrest, M., Lasslop, G., Li, F., Mangeon, S., Melton, J.R., Yue, C. and Randerson, J.T. 2017. A Human-Driven Decline in Global Burned Area. *Science.* **356**(6345), p1356.10.1126/science.aal4108

Andela, N., Morton, D.C., Giglio, L., Paugam, R., Chen, Y., Hantson, S., van der Werf, G.R. and Randerson, J.T. 2019. The Global Fire Atlas of Individual Fire Size, Duration, Speed and Direction. *Earth Syst. Sci. Data.* **11**(2), pp.529-552.10.5194/essd-11-529-2019

Andriesse, J.P. 1988. *Nature and Management of Tropical Peat Soils.* [Online]. Food and Agriculture Organization of the United Nations. Available from: http://www.fao.org/3/x5872e/x5872e00.htm

Anggoro. 2016. *Saksi Ahli Dishutbun Pelalawan: Kebakaran Pt Lih Karena Api Lompat.* [Online]. Available from: https://riau.antaranews.com/berita/70206/saksi-ahli-dishutbun-pelalawan-kebakaran-pt-lih-karena-api-lompat

Anggoro. 2020. Riau Miliki Dua Hutan Adat Yang Diakui Pemerintah. *ANTARA*. 29 Februari 2020 *[Riau has two customary forests recognized by the government]*. Available from: https://www.antaranews.com/berita/1326538/riau-miliki-dua-hutan-adat-yang-diakui-pemerintah

Applegate, G., Chokkalingam, U. and Suyanto, S. 2001. *The Underlying Causes and Impacts of Fires in South-East Asia—Final Report.*

Austin, K.G., Schwantes, A., Gu, Y. and Kasibhatla, P.S. 2019. What Causes Deforestation in Indonesia? *Environmental Research Letters.* **14**(2), p024007.10.1088/1748-9326/aaf6db

Bappenas. 2015. *Analisis Provinsi Riau.*

Barbosa, P., Caetano, M.R. and Santos, T.G. 2000. Detection of Changes in Forest Landcover Type after Fires in Portugal. *International Archieves of Photogrammetry and Remote Sensing.* (XXXIII),

BBC. 2019. *Asap Kebakaran Hutan Di Jambi 'Membuat Langit Menjadi Merah'.* [Online]. [Accessed 25 June 2020]. Available from: https://www.bbc.com/indonesia/indonesia-49787843

Bodí, M.B., Martin, D.A., Balfour, V.N., Santín, C., Doerr, S.H., Pereira, P., Cerdà, A. and Mataix-Solera, J. 2014. Wildland Fire Ash: Production, Composition and Eco-Hydro-Geomorphic Effects. *Earth-Science Reviews.* **130**, pp.103-127.https://doi.org/10.1016/j.earscirev.2013.12.007

Bowen, M.R., Bompard, J.M., Anderson, I.P., Guizol, P. and Gouyon, A. 2001. *Anthropogenic Fires in Indonesia: A View from Sumatra.* Huntington, New York: Nova Science Publishers.

Bowman, D.M.J.S., Balch, J.K., Artaxo, P., Bond, W.J., Carlson, J.M., Cochrane, M.A., D'Antonio, C.M., Defries, R.S., Doyle, J.C., Harrison, S.P., Johnston, F.H., Keeley, J.E., Krawchuk, M.A., Kull, C.A., Marston, J.B., Moritz, M.A., Prentice, I.C., Roos, C.I., Scott, A.C., Swetnam, T.W., van der Werf, G.R. and Pyne, S.J. 2009. Fire in the Earth System. *Science (New York, N.Y.).* **324**(5926), pp.481-484.10.1126/science.1163886

BPS. 2021. *Statistics of Forestry.* [Online]. [Accessed 17 January]. Available from: https://www.bps.go.id/subject/60/kehutanan.html

BPS Riau. 2020. *Provinsi Riau Dalam Angka 2020.* BPS Riau.

Brandt, J., Primdahl, J. and Reenberg, A. 1999. Rural Land-Use and Landscape Dynamics - Analysis of 'Driving Forces' in Space and Time. In: Krönert, R., et al. eds. *Land-Use Changes and Their Environmental Impact in Rural Areas in Europe.* Paris: Unesco, pp.81-102.

BRG. 2019. *Three Years of Peatland Restoration in Indonesia Report.* Peat Restoration Agency of The Republic of Indonesia.

Wildfire. s.v.

Bürgi, M., Hersperger, A.M. and Schneeberger, N. 2004. Driving Forces of Landscape Change - Current and New Directions. *Landscape Ecology.* **19**(8), pp.857-868.10.1007/s10980-005-0245-3

Byram, G.M. 1959. Combustion of Forest Fuels. In: Davis, K.P. ed. *Forest Fire: Control and Use.* New York: McGraw-Hill, pp.61-89.

Chuvieco, E., De Santis, A., Riaño, D. and Halligan, K. 2007. Simulation Approaches for Burn Severity Estimation Using Remotely Sensed Images. *Fire Ecology.* **3**(1), pp.129-150.10.4996/fireecology.0301129

Chuvieco, E. and Martín, M. 1994. Global Fire Mapping and Fire Danger Estimation Using Avhrr Images. *Photogrammetric Engineering and Remote Sensing.* **60**,

Chuvieco, E., Mouillot, F., van der Werf, G.R., San Miguel, J., Tanase, M., Koutsias, N., García, M., Yebra, M., Padilla, M., Gitas, I., Heil, A., Hawbaker, T.J. and Giglio, L. 2019. Historical Background and Current Developments for Mapping Burned Area from Satellite Earth Observation. *Remote Sensing of Environment.* **225**, pp.45-64.https://doi.org/10.1016/j.rse.2019.02.013

Chuvieco, E., Riaño, D., Danson, F.M. and Martin, P. 2006. Use of a Radiative Transfer Model to Simulate the Postfire Spectral Response to Burn Severity. *Journal of Geophysical Research: Biogeosciences.* **111**(G4).https://doi.org/10.1029/2005JG000143

Climate-Data.org. *Riau Climate.* [Online]. [Accessed 21 June 2020]. Available from: https://en.climate-data.org/asia/indonesia/riau-1208/

Cochrane, M.A. 2003. Fire Science for Rainforests. *Nature.* **421**(6926), pp.913-919.10.1038/nature01437

Cochrane, M.A. 2009. Fire in the Tropics. In: Cochrane, M.A. ed. *Tropical Fire Ecology: Climate Change, Land Use, and Ecosystem Dynamics.* Berlin, Heidelberg: Springer Berlin Heidelberg, pp.1-23.

Cochrane, M.A. and Schulze, M.D. 1999. Fire as a Recurrent Event in Tropical Forests of the Eastern Amazon: Effects on Forest Structure, Biomass, and Species Composition. *Biotropica.* **31**(1), pp.2-16.10.2307/2663955

Countryman, C.M. 1972. *The Fire Environment Concept.* Berkeley, CA: USDA Forest Service, Pacific Southwest Forest and Range Experiment Station.

Crippa, P., Castruccio, S., Archer-Nicholls, S., Lebron, G.B., Kuwata, M., Thota, A., Sumin, S., Butt, E., Wiedinmyer, C. and Spracklen, D.V. 2016. Population Exposure to Hazardous Air Quality Due to the 2015 Fires in Equatorial Asia. *Sci Rep.* **6**, p37074.10.1038/srep37074

Davies, J. and R. Davies, D. 2009. *Earth's Surface Heat Flux.*

Dennis, R.A., Mayer, J., Applegate, G., Chokkalingam, U., Colfer, C., Kurniawan, I., Lachowski, H., Maus, P., Permana, R.P., Ruchiat, Y., Stolle, F., Suyanto and Tomich, T.P. 2005. Fire, People and Pixels: Linking Social Science and Remote Sensing to Understand Underlying Causes and Impacts of Fires in Indonesia. *Human Ecology.* **33**(4), pp.465-504.10.1007/s10745-005-5156-z

Dishut Riau. 2014. *Statistik Dinas Kehutanan Provinsi Riau Tahun 2013.* Pekanbaru.

Dohong, A., Aziz, A.A. and Dargusch, P. 2017. A Review of the Drivers of Tropical Peatland Degradation in South-East Asia. *Land Use Policy.* **69**(Supplement C), pp.349-360.10.1016/j.landusepol.2017.09.035

Edwards, R.B. 2019. *Export Agriculture and Rural Poverty : Evidence from Indonesian Palm Oil.* [Manuscript]. At*:* Brisbane.

Ekadinata, A.E. and Dewi, S. 2011. *Estimating Losses in Aboveground Carbon Stock from Land-Use and Land-Cover Changes in Indonesia (1990, 2000, 2005).* Bogor: World Agroforestry Centre (ICRAF) Southeast Asia Program.

Eva, H. and Lambin, E.F. 1998. Remote Sensing of Biomass Burning in Tropical Regions. *Remote Sensing of Environment.* **64**(3), pp.292-315.10.1016/s0034-4257(98)00006-6

Eva, H. and Lambin, E.F. 2000. Fires and Land-Cover Change in the Tropics: A Remote Sensing Analysis at the Landscape Scale. *Journal of Biogeography.* **27**(3), pp.765-776

Fanin, T. and van der Werf, G.R. 2015. Relationships between Burned Area, Forest Cover Loss, and Land Cover Change in the Brazilian Amazon Based on Satellite Data. *Biogeosciences.* **12**(20), pp.6033-6043.10.5194/bg-12-6033-2015

Fanin, T. and van der Werf, G.R. 2017. Precipitation–Fire Linkages in Indonesia (1997–2015). *Biogeosciences.* **14**(18), pp.3995-4008.10.5194/bg-14-3995-2017

Field, R.D., van der Werf, G.R., Fanin, T., Fetzer, E.J., Fuller, R., Jethva, H., Levy, R., Livesey, N.J., Luo, M., Torres, O. and Worden, H.M. 2016. Indonesian Fire Activity and Smoke Pollution in 2015 Show Persistent Nonlinear Sensitivity to El Nino-Induced Drought. *Proc Natl Acad Sci U S A.* **113**(33), pp.9204-9209.10.1073/pnas.1524888113

Field, R.D., van der Werf, G.R. and Shen, S.S.P. 2009. Human Amplification of Drought-Induced Biomass Burning in Indonesia since 1960. *Nature Geosci.* **2**(3), pp.185-188.http://www.nature.com/ngeo/journal/v2/n3/suppinfo/ngeo443_S1.html

Gaveau, D.L.A., Salim, M.A., Hergoualc'h, K., Locatelli, B., Sloan, S., Wooster, M., Marlier, M.E., Molidena, E., Yaen, H., DeFries, R., Verchot, L., Murdiyarso, D., Nasi, R., Holmgren, P. and Sheil, D. 2014. Major Atmospheric Emissions from Peat Fires in Southeast Asia During Non-Drought Years: Evidence from the 2013 Sumatran Fires. *Sci Rep.* **4**, p6112.10.1038/srep06112

Gaveau, D.L.A., Sheil, D., Husnayaen, Salim, M.A., Arjasakusuma, S., Ancrenaz, M., Pacheco, P. and Meijaard, E. 2016. Rapid Conversions and

Avoided Deforestation: Examining Four Decades of Industrial Plantation Expansion in Borneo. *Scientific Reports.* **6**, p32017.10.1038/srep32017

https://www.nature.com/articles/srep32017#supplementary-information

Giglio, L. 2010. *Modis Collection 5 Active Fire Product User's Guide Version 2.4.* [Manuscript]. At.

Giglio, L., Descloitres, J., Justice, C.O. and Kaufman, Y.J. 2003. An Enhanced Contextual Fire Detection Algorithm for Modis. *Remote Sensing of Environment.* **87**(2-3), pp.273-282.10.1016/s0034-4257(03)00184-6

Giglio, L., Loboda, T., Roy, D.P., Quayle, B. and Justice, C.O. 2009. An Active-Fire Based Burned Area Mapping Algorithm for the Modis Sensor. *Remote Sensing of Environment.* **113**(2), pp.408-420.https://doi.org/10.1016/j.rse.2008.10.006

Giglio, L., Schroeder, W. and Justice, C.O. 2016. The Collection 6 Modis Active Fire Detection Algorithm and Fire Products. *Remote Sensing of Environment.* **178**, pp.31-41.https://doi.org/10.1016/j.rse.2016.02.054

Giglio, L., van der Werf, G.R., Randerson, J., Collatz, G. and Kasibhatla, P. 2006. Global Estimation of Burned Area Using Modis Active Fire Observations. *Atmospheric Chemistry and Physics.* **5**.10.5194/acp-6-957-2006

Gillison. 2001. *Vegetation Survey and Habitat Assesment of the Tesso Nilo Forest Complex.* Center for Biodiversity Management.

Goldammer, J.G. 2013. *Vegetation Fires and Global Change*. Kessel Publishing. Available from: https://gfmc.online/wp-content/uploads/Vegetation-Fires-Global-Change-UN-White-Paper-GFMC-2013.pdf

Goverment of Indonesia. Peraturan Pemerintah Nomor 21 Tahun 1970 Tentang Hak Pengusahaan Hutan Dan Hak Pemungutan Hasil Hutan. [Government Regulation Number 21 Year 1970 on Forest Exploitation and Harvesting Rights]. Available from: https://peraturan.bpk.go.id/Home/Download/60086/pp%20no%20021%20tahun%201970.pdf

Goverment of Indonesia. Undang-Undang Nomor 4 Tahun 1982 Tentang Ketentuan-Ketentuan Pokok Pengelolaan Lingkungan Hidup. [Regulations Number 4 Year 1982 on Principle of Natural Development .]. Available from: http://sipongi.menlhk.go.id/cms/images/files/1022.pdf

Goverment of Indonesia. Peraturan Pemerintah (Pp) Nomor 28 Tahun 1985 Tentang Perlindungan Hutan. [Government Regulation Number 28 Year 1985 on Forest Protection]. Available from: http://sipongi.menlhk.go.id/cms/images/files/1038.pdf

Goverment of Indonesia. Undang-Undang Nomor 41 Tahun 1999 Tentang Kehutanan. [Regulation Number 41 Year 1999 on Forestry]. Available from:

http://kpa.or.id/publikasi/download/b29bc-uu-no-41-tahun-1999-tentang-kehutanan.pdf

Goverment of Indonesia. Peraturan Pemerintah No 4 Tahun 2001 Tentang Pengendalian Kerusakan Dan Atau Pencemaran Lingkungan Hidup Yang Berkaitan Dengan Kebakaran Hutan Dan Atau Lahan. [Government Regulation No. 4 of 2001 on Control of Environmental Degradation and/or Pollution Related to Forest and/or Land Fires]. Available from: http://sipongi.menlhk.go.id/cms/images/files/1041.pdf

Goverment of Indonesia. Undang-Undang Dasar 1945. [The Constitution of the Republic of Indonesia of 1945].

Goverment of Indonesia. Peraturan Pemerintah No 45 Tahun 2004 Tentang Perlindungan Hutan. [Government Regulation No 45 Year 2004 on Forest Protection]. Available from: http://sipongi.menlhk.go.id/cms/images/files/1043.pdf

Goverment of Indonesia. Undang-Undang No 24 Tahun 2007 Tentang Penanggulangan Bencana. [Regulation No 24 Year 2007 on Disaster Management]. Available from: https://www.bnpb.go.id/ppid/file/UU_24_2007.pdf

Goverment of Indonesia. Undang-Undang Nomor 32 Tahun 2009 Tentang Perlindungan Dan Pengelolaan Lingkungan Hidup. [Regulation No. 32/2009 on Environmental Protection and Management.]. Available from: http://faolex.fao.org/docs/pdf/ins97643.pdf

Goverment of Indonesia. Instruksi Presiden No 11 Tahun 2011 Tentang Penundaan Pemberian Izin Baru Dan Penyempurnaan Tata Kelola Hutan Alam Primer Dan Lahan Gambut. [Presidential Instruction Number 10 of 2011 on Postponement of Granting of New Permits and Improving management of Primary Natural Forests and Peatlands]. Available from: http://ditjenpp.kemenkumham.go.id/arsip/ln/2011/ips10-2011.pdf

Goverment of Indonesia. Undang-Undang Nomor 12 Tahun 2011 Tentang Pembentukan Peraturan Perundang-Undangan [Regulation Number 12 Year 2011 on Concerning Making Rules]. Available from: http://bphn.go.id/data/documents/11uu012.pdf

Goverment of Indonesia. Putusan Mahkamah Konstitusi Nomor 35/Puu-X/2012. [Constitutional Court Decision Number 35/PUU-X/2012]. Available from: https://www.aman.or.id/wp-content/uploads/2018/05/putusan_sidang_35-PUU-2012-Kehutanan-telah-ucap-16-Mei-2013.pdf

Goverment of Indonesia. Undang-Undang Nomor 18 Tahun 2013 Tentang Pencegahan Dan Pemberantasan Perusakan Hutan. [Regulation No 18 Year 2013 Prevention and Eradication of Forest Destruction]. Available from: http://www.dpr.go.id/dokjdih/document/uu/UU_2013_18.pdf

Goverment of Indonesia. Peraturan Pemerintah Nomor 71 Tahun 2014 Tentang Perlindungan Dan Pengelolaan Ekosistem Gambut. [Peat Ecosystem Protection and Management]. Available from: http://pkgppkl.menlhk.go.id/v0/wp-content/uploads/2018/10/PP-Nomor-71-Tahun-2014-tentang-PPE-Gambut.pdf

Goverment of Indonesia. Undang-Undang No 26 Tahun 2014 Tentang Pengesahan Persetujuan Asean Tentang Pencemaran Asap Lintas Batas. [Regulation No 26 year 2014 on the Adoption of ASEAN Agreement on Transboundary Haze Pollution]. Available from: https://sipuu.setkab.go.id/PUUdoc/174248/UU%2026%20Tahun%202014.pdf

Goverment of Indonesia. 2014c. *Undang-Undang No 39 Tahun 2014 Tentang Perkebunan*. Available from: http://www.jdih.kemenkeu.go.id/fullText/2014/39TAHUN2014UU.pdf

Goverment of Indonesia. Instruksi Presiden No 5 Tahun 2019 Tentang Penghentian Pemberian Izin Baru Dan Penyempurnaan Tata Kelola Hutan Alam Primer Dan Lahan Gambut. [Presidential Instruction No 5 Year 2010 on Termination of Granting New Licenses and Improvement of Natural Primary Forest and Peatland Governance]. Available from: https://gapki.id/wp-content/uploads/2019/08/Inpres-Nomor-5-Tahun-2019-Salinan.pdf

Goverment of Indonesia. Instruksi Presiden Nomor 3 Tahun 2020 Penanggulangan Kebakaran Hutan Dan Lahan. [Presidential Instruction Number 3 of 2020 on Mitigation of Forest and Land Fires.]. Available from: https://setkab.go.id/presiden-teken-inpres-nomor-3-tahun-2020-tentang-penanggulangan-karhutla/

Greenpeace. 2013. *An Impending Storm - Impact of Deforestration on Weather Patterns and Agriculture.Pdf>.*

GSARS.org. 2016. *Information on Land in the Context of Agricultural Statistisc.*

H S U. 2016. *Modis Bands.* Humbolt State University.

Hansen, M.C., Defries, R.S., Townshend, J.R.G. and Sohlberg, R. 2000. Global Land Cover Classification at 1 Km Spatial Resolution Using a Classification Tree Approach. *International Journal of Remote Sensing.* **21**(6-7), pp.1331-1364.10.1080/014311600210209

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O. and Townshend, J.R. 2013. High-Resolution Global Maps of 21st-Century Forest Cover Change. *Science.* **342**(6160), pp.850-853.10.1126/science.1244693

Hansen, M.C., Stehman, S.V. and Potapov, P.V. 2010. Quantification of Global Gross Forest Cover Loss. *Proc Natl Acad Sci U S A.* **107**(19), pp.8650-8655.10.1073/pnas.0912668107

Hantson, S., Padilla, M., Corti, D. and Chuvieco, E. 2013. *Strengths and Weaknesses of Modis Hotspots to Characterize Global Fire Occurrence.*

Hardy, C.C. 2005. Wildland Fire Hazard and Risk: Problems, Definitions, and Context. *Forest Ecology and Management.* **211**(1-2), pp.73-82.10.1016/j.foreco.2005.01.029

Harja, D., Dewi, S., Heryawan, F. and van Noordwijk, M. 2011. *Forest Carbon-Stock Estimates Based on National Forest Inventory Data.*

Harris, N.L., Goldman, E., Gabris, C., Nordling, J., Minnemeyer, S., Ansari, S., Lippmann, M., Bennett, L., Raad, M., Hansen, M.C. and Potapov, P.V. 2017. Using Spatial Statistics to Identify Emerging Hot Spots of Forest Loss. *Environmental Research Letters.* **12**(2), p024012.10.1088/1748-9326/aa5a2f

Harrison, M.E., Ottay, J.B., D'Arcy, L.J., Cheyne, S.M., Anggodo, Belcher, C., Cole, L., Dohong, A., Ermiasi, Y., Feldpausch, T., Gallego-Sala, A., Gunawan, A., Höing, A., Husson, S.J., Kulu, I.P., Soebagio, S.M., Mang, S., Mercado, L., Morrogh-Bernard, H.C., Page, S.E., Priyanto, R., Ripoll Capilla, B., Rowland, L., Santos, E.M., Schreer, V., Sudyana, I.N., Taman, S.B.B., Thornton, S.A., Upton, C., Wich, S.A. and van Veen, F.J.F. 2019. Tropical Forest and Peatland Conservation in Indonesia: Challenges and Directions. *People and Nature.* **n/a**(n/a).10.1002/pan3.10060

Harrison, M.E., Page, S.E. and Limin, S. 2009. The Global Impact of Indonesian Forest Fires. *Biologist.* **56**, pp.156-163

Hersperger, A.M., Gennaio, M.-P., Verburg, P.H. and Bürgi, M. 2010. Linking Land Change with Driving Forces and Actors: Four Conceptual Models. *Ecology and Society.* **15**(4).10.5751/es-03562-150401

Hislop, S., Haywood, A., Jones, S., Soto-Berelov, M., Skidmore, A. and Nguyen, T.H. 2020. A Satellite Data Driven Approach to Monitoring and Reporting Fire Disturbance and Recovery across Boreal and Temperate Forests. *International Journal of Applied Earth Observation and Geoinformation.* **87**, p102034.https://doi.org/10.1016/j.jag.2019.102034

Hudak, A.T., Robichaud, P., Evans, J., Clark, J., Lannom, K., Morgan, P. and Stone, C. 2004. Field Validation of Burned Area Reflectance Classification (Barc) Products for Post Fire Assessment.

Huijnen, V., Wooster, M.J., Kaiser, J.W., Gaveau, D.L.A., Flemming, J., Parrington, M., Inness, A., Murdiyarso, D., Main, B. and van Weele, M. 2016. Fire Carbon Emissions over Maritime Southeast Asia in 2015 Largest since 1997. *Scientific Reports.* **6**, p26886.10.1038/srep26886

https://www.nature.com/articles/srep26886#supplementary-information

Izquierdo, N.L. 2017. *Formation of Tropical Peatlands.* [Online]. Available from: https://www.grida.no/resources/12531

James, S.R., Dennell, R.W., Gilbert, A.S., Lewis, H.T., Gowlett, J.A.J., Lynch, T.F., McGrew, W.C., Peters, C.R., Pope, G.G. and Stahl, A.B. 1989. Hominid Use of Fire in the Lower and Middle Pleistocene: A Review of the Evidence [and Comments and Replies]. *Current Anthropology.* **30**(1), pp.1-26.10.2307/2743299

Jayarathne, T., Stockwell, C., Gilbert, A., Daugherty, K., Cochrane, M.A., Ryan, K., Putra, E., Saharjo, B., Dwi Nurhayati, A., Albar, I., Yokelson, R. and Stone, E. 2018. Chemical Characterization of Fine Particulate Matter Emitted by Peat Fires in Central Kalimantan, Indonesia, During the 2015 El Niño. *Atmospheric Chemistry and Physics.* **18**, pp.2585-2600.10.5194/acp-18-2585-2018

Johnson, E.A. and Gutsell, S.L. 1994. Fire Frequency Models, Methods and Interpretations. *Advances in Ecological Research.* **25**,

Joosten, H. and Clarke, D. 2002. *Wise Use of Mires and Peatlands.* International Mire Conservation Group and International Peat Society.

Juárez-Orozco, S.M., Siebe, C. and Fernández y Fernández, D. 2017. Causes and Effects of Forest Fires in Tropical Rainforests: A Bibliometric Approach. *Tropical Conservation Science.* **10**, p1940082917737207.10.1177/1940082917737207

Justice, C.O., Giglio, L., Korontzi, S., Owens, J., Morisette, J.T., Roy, D., Descloitres, J., Alleaume, S., Petitcolin, F. and Kaufman, Y. 2002a. The Modis Fire Products. *Remote Sensing of Environment.* **83**(1), pp.244-262.https://doi.org/10.1016/S0034-4257(02)00076-7

Justice, C.O., Townshend, J.R.G., Vermote, E.F., Masuoka, E., Wolfe, R.E., Saleous, N., Roy, D.P. and Morisette, J.T. 2002b. An Overview of Modis Land Data Processing and Product Status. *Remote Sensing of Environment.* **83**(1), pp.3-15.https://doi.org/10.1016/S0034-4257(02)00084-6

Kasischke, E.S., Hewson, J.H., Stocks, B., van der Werf, G. and Randerson, J. 2003. The Use of Atsr Active Fire Counts for Estimating Relative Patterns of Biomass Burning – a Study from the Boreal Forest Region. *Geophysical Research Letters.* **30**(18).https://doi.org/10.1029/2003GL017859

Kaufman, Y.J., Justice, C.O., Flynn, L.P., Kendall, J.D., Prins, E.M., Giglio, L., Ward, D.E., Menzel, W.P. and Setzer, A.W. 1998. Potential Global Fire Monitoring from Eos-Modis. *Journal of Geophysical Research: Atmospheres.* **103**(D24), pp.32215-32238.10.1029/98JD01644

Keenan, R., Reams, G., Frédéric, A., Freitas, J.V., Grainger, A. and Lindquist, E. 2015. Dynamics of Global Forest Area: Results from the Fao Global Forest Resources Assessment 2015. *Forest Ecology and Management.* **352**, Kiely, L., Spracklen, D.V., Wiedinmyer, C., Conibear, L., Reddington, C.L., Archer-Nicholls, S., Lowe, D., Arnold, S.R., Knote, C., Khan, M.F., Latif, M.T., Kuwata, M., Budisulistiorini, S.H. and Syaufina, L. 2019. New Estimate of Particulate Emissions from Indonesian Peat Fires in 2015. *Atmos. Chem. Phys.* **19**(17), pp.11105-11121.10.5194/acp-19-11105-2019

Kinnaird, M. and O'Brien, T. 1998. Ecological Effects of Wildfire on Lowland Rainforest in Sumatra. *Conservation Biology.* **12**, pp.954-956.10.1046/j.1523-1739.1998.00005.x

Koplitz, S.N., Mickley, L.J., Marlier, M.E., Buonocore, J.J., Kim, P.S., Liu, T., Sulprizio, M.P., DeFries, R.S., Jacob, D.J., Schwartz, J., Pongsiri, M. and Myers, S.S. 2016. Public Health Impacts of the Severe Haze in Equatorial Asia in September–October 2015: Demonstration of a New Framework for Informing Fire Management Strategies to Reduce Downwind Smoke Exposure. *Environmental Research Letters.* **11**(9), p094023.10.1088/1748-9326/11/9/094023

Langner, A., Miettinen, J. and Siegert, F. 2007. Land Cover Change 2002–2005 in Borneo and the Role of Fire Derived from Modis Imagery. *Global Change Biology.* **13**(11), pp.2329-2340.10.1111/j.1365-2486.2007.01442.x

Langner, A. and Siegert, F. 2009. Spatiotemporal Fire Occurrence in Borneo over a Period of 10 Years. *Global Change Biology.* **15**(1), pp.48-62.10.1111/j.1365-2486.2008.01828.x

Lappalainen. 1996. *Global Peat Map.* [Online]. Available from: https://peatlands.org/peatlands/where-can-peatlands-be-found/

Lavorel, S., Flannigan, M.D., Lambin, E.F. and Scholes, M.C. 2006. Vulnerability of Land Systems to Fire: Interactions among Humans, Climate, the Atmosphere, and Ecosystems. *Mitigation and Adaptation Strategies for Global Change.* **12**(1), pp.33-53.10.1007/s11027-006-9046-5

Lentile, L., Holden, Z., Smith, A., Falkowski, M., Hudak, A.T., Morgan, P., Lewis, S., Gessler, P. and Benson, N. 2006. Remote Sensing Techniques to Assess Active Fire Characteristics and Post-Fire Effects. *International Journal of Wildland Fire.* **15**.10.1071/WF05097

Liu, Y., Dai, Q., Liu, J., Liu, S. and Yang, J. 2014. Study of Burn Scar Extraction Automatically Based on Level Set Method Using Remote Sensing Data. *PloS one.* **9**(2), pp.e87480-e87480.10.1371/journal.pone.0087480

Margono, B.A., Potapov, P.V., Turubanova, S., Stolle, F. and Hansen, M.C. 2014. Primary Forest Cover Loss in Indonesia over 2000–2012. *Nature Climate Change.* **4**(8), pp.730-735.10.1038/nclimate2277

Margono, B.A., Usman, A.B., Budiharto and Sugardiman, R.A. 2016. Indonesia’s Forest Resource Monitoring. *Indonesian Journal of Geography; Vol 48, No 1 (2016): Indonesian Journal of Geography.*10.22146/ijg.12496

Marlier, M.E., DeFries, R.S., Kim, P.S., Koplitz, S.N., Jacob, D.J., Mickley, L.J. and Myers, S.S. 2015. Fire Emissions and Regional Air Quality Impacts from Fires in Oil Palm, Timber, and Logging Concessions in Indonesia. *Environmental Research Letters.* **10**(8), p085005.10.1088/1748-9326/10/8/085005

Marlier, M.E., DeFries, R.S., Voulgarakis, A., Kinney, P.L., Randerson, J.T., Shindell, D.T., Chen, Y. and Faluvegi, G. 2013. El Niño and Health Risks from Landscape Fire Emissions in Southeast Asia. *Nature climate change.* **3**, pp.131-136.10.1038/nclimate1658

Martín, M.P., Ceccato, P., Flasse, S. and Downey, I. 1999. Fire Detection and Fire Growth Monitoring Using Satellite Data. In: Chuvieco, E. ed. *Remote Sensing of Large Wildfires: In the European Mediterranean Basin.* Berlin, Heidelberg: Springer Berlin Heidelberg, pp.101-122.

Miettinen, J. and Liew, S.C. 2005. Connection between Fire and Land Cover Change in Southeast Asia: A Remote Sensing Case Study in Riau, Sumatra. *International Journal of Remote Sensing.* **26**(6), pp.1109-1126.10.1080/01431160512331326756

Mikolajczyk, J., Bielecki, Z., Bugajski, M., Piotrowski, J., Wojtas, J., Gawron, W., Szabra, D. and Prokopiuk, A. 2017. Analysis of Free-Space Optics Development. *Metrology and Measurement Systems.* **24**.10.1515/mms-2017-0060

Mitchard, E.T.A. 2018. The Tropical Forest Carbon Cycle and Climate Change. *Nature.* **559**(7715), pp.527-534.10.1038/s41586-018-0300-2

MoEF. 2015. *Statistik Kementrian Lingkungan Hidup Dan Kehutanan Tahun 2014.* Ministry of Environment and Forestry.

MoEF. 2020. *Statistik Kementrian Lingkungan Hidup Dan Kehutanan Tahun 2019.* Ministry of Environment and Forestry.

MoF. Keputusan Direktur Jenderal Perlindungan Hutan Dan Kelestarian Alam Nomor 244 Tahun 1994 Tentang Petunjuk Teknis Pemadaman Kebakaran Hutan. [Decree of the Director General of Forest Protection and Nature Conservation Number 244 of 1994 Concerning Technical Guidelines for Combating Forest Fires].

MoF. 2002. *Data Dan Informasi Kehutanan Propinsi Riau 2002.* Pusat Inventarisasi dan Statistik Kehutanan, Badan Planologi Kehutanan, Departemen Kehutanan.

MoF. Peraturan Menteri Kehutanan No. P12/Menhut-Ii/2009 Tentang Pengendalian Kebakaran Hutan. [The Ministry of Forestry Regulation No. P12/Menhut-II/2009 on the Control of Forest Fires]. Available from: http://sipongi.menlhk.go.id/cms/images/files/38.pdf

Molnar, A. and Mcminn, R.G. 1960. The Origin of Basal Scars in the British Columbia Interior White Pine Type. *Forestry Chronicle.* **36**, pp.50-60

Moritz, M.A., Morais, M.E., Summerell, L.A., Carlson, J.M. and Doyle, J. 2005. Wildfires, Complexity, and Highly Optimized Tolerance. *Proceedings* *of the National Academy of Sciences of the United States of America.* **102**(50), p17912.10.1073/pnas.0508985102

Mouillot, F. and Field, C.B. 2005. Fire History and the Global Carbon Budget: A 1°× 1° Fire History Reconstruction for the 20th Century. *Global Change Biology.* **11**(3), pp.398-420.10.1111/j.1365-2486.2005.00920.x

Msofe, N.K., Sheng, L. and Lyimo, J. 2019. Land Use Change Trends and Their Driving Forces in the Kilombero Valley Floodplain, Southeastern Tanzania. *Sustainability.* **11**(2).10.3390/su11020505

Murdiyarso, D. and Lebel, L. 2007a. Local to Global Perspectives on Forest and Land Fires in Southeast Asia. *Mitigation and Adaptation Strategies for Global Change.* **12**(1), pp.3-11.10.1007/s11027-006-9055-4

Murdiyarso, D. and Lebel, L. 2007b. Southeast Asian Fire Regimes and Land Development Policy. In: Canadell, J.G., et al. eds. *Terrestrial Ecosystems in a Changing World.* Berlin, Heidelberg: Springer Berlin Heidelberg, pp.261-271.

Murdiyarso, D. and Lebel, L. 2007c. Southeast Asian Fire Regimes and Land Development Policy. pp.261-271.10.1007/978-3-540-32730-1_21

NASA. *The Enhanced Thematic Mapper Plus* [Online]. [Accessed June 23, 2020]. Available from: https://landsat.gsfc.nasa.gov/the-enhanced-thematic-mapper-plus/

NASA LAADS DAAC. 2020. *Terra & Aqua Moderate Resolution Imaging Spectroradiometer (Modis).* [Online]. [Accessed 22 June 2020]. Available from: https://ladsweb.modaps.eosdis.nasa.gov/missions-and-measurements/modis/

Nurhidayah, L. and Djalante, R. 2017. Examining the Adequacy of Legal and Institutional Frameworks of Land and Forest Fire Management from National to Community Levels in Indonesia. pp.157-187.

Nurrochmat, D.R. and Abdullah, L. 2014. Memanfaatkan Hutan Mengurangi Emisi. *Risalah Kebijakan Pertanian dan Lingkungan.* **1**(1), pp.18-13.https://doi.org/10.29244/jkebijakan.v1i1.10274

Nurrochmat, D.R., Darusman, D. and Ekayani, M. 2016. *Kebijakan Pembangunan Kehutanan Dan Lingkungan. Teori Dan Implentasi.* Bogor: IPB Press.

Olson, D.M. and Dinerstein, E. 2002. The Global 200: Priority Ecoregions for Global Conservation. *Annals of the Missouri Botanical Garden.* **89**(2), pp.199-224.10.2307/3298564

Olson, D.M., Dinerstein, E., Wikramanayake, E.D., Burgess, N.D., Powell, G.V.N., Underwood, E.C., D'Amico, J.A., Itoua, I., Strand, H.E., Morrison, J.C., Loucks, C.J., Allnutt, T.F., Ricketts, T.H., Kura, Y., Lamoreux, J.F., Wettengel, W.W., Hedao, P. and Kassem, K.R. 2001. Terrestrial Ecoregions of the World: A New Map of Life on Earth: A New Global Map of Terrestrial

Ecoregions Provides an Innovative Tool for Conserving Biodiversity. *BioScience.* **51**(11), pp.933-938.10.1641/0006-3568(2001)051[0933:TEOTWA]2.0.CO;2

Page, S.E., Banks, C. and Rieley, J. 2007. Tropical Peatlands: Distribution, Extent and Carbon Storage-Uncertainties and Knowledge Gaps. **2**,

Page, S.E., Hoscilo, A., Langner, A., Tansey, K., Siegert, F., Limin, S. and Rieley, J. 2009. Tropical Peatland Fires in Southeast Asia. In: Cochrane, M.A. ed. *Tropical Fire Ecology: Climate Change, Land Use, and Ecosystem Dynamics.* Berlin, Heidelberg: Springer Berlin Heidelberg, pp.263-287.

Page, S.E., Hoscilo, A., Wösten, H., Jauhiainen, J., Silvius, M., Rieley, J., Ritzema, H., Tansey, K., Graham, L., Vasander, H. and Limin, S. 2008. Restoration Ecology of Lowland Tropical Peatlands in Southeast Asia: Current Knowledge and Future Research Directions. *Ecosystems.* **12**(6), pp.888-905.10.1007/s10021-008-9216-2

Page, S.E., Rieley, J., Hoscilo, A., Spessa, A.C. and Weber, U. 2013. Current Fire Regimes, Impacts and the Likely Changes – Iv: Tropical Southeast Asia Introduction. *Vegetation Fires and Global Changes - Challanges for Concerted International Action.*

Page, S.E., Rieley, J. and Wüst, R. 2006. Chapter 7 Lowland Tropical Peatlands of Southeast Asia. *Peatlands: Evolution and Records of Environmental and Climate Changes.* **9**.10.1016/S0928-2025(06)09007-9

Page, S.E., Rieley, J.O. and Banks, C.J. 2011. Global and Regional Importance of the Tropical Peatland Carbon Pool. *Global Change Biology.* **17**(2), pp.798-818.https://doi.org/10.1111/j.1365-2486.2010.02279.x

Page, S.E., Siegert, F., Rieley, J.O., Boehm, H.D., Jaya, A. and Limin, S. 2002. The Amount of Carbon Released from Peat and Forest Fires in Indonesia During 1997. *Nature.* **420**(6911), pp.61-65.10.1038/nature01131

Pereira, J.M.C. 1999. A Comparative Evaluation of Noaa/Avhrr Vegetation Indexes for Burned Surface Detection and Mapping. *IEEE Transactions on Geoscience and Remote Sensing.* **37**(1), pp.217-226.10.1109/36.739156

Pereira, J.M.C., Chuvieco, E., Beaudoin, A. and Desbois, N. 1997. *Remote Sensing of Burned Areas: A Review. A Review of Remote Sensing Methods for the Study of Large Wildland Fires.*

Pereira, J.M.C., Mota, B., Privette, J.L., Caylor, K.K., Silva, J.M.N., Sá, A.C.L. and Ni-Meister, W. 2004. A Simulation Analysis of the Detectability of Understory Burns in Miombo Woodlands. *Remote Sensing of Environment.* **93**(3), pp.296-310.https://doi.org/10.1016/j.rse.2004.01.009

Pielke, R.A., Pitman, A., Niyogi, D., Mahmood, R., McAlpine, C., Hossain, F., Goldewijk, K.K., Nair, U., Betts, R., Fall, S., Reichstein, M., Kabat, P. and de Noblet, N. 2011. Land Use/Land Cover Changes and Climate: Modeling Analysis and Observational Evidence. *Wiley Interdisciplinary Reviews: Climate Change.* **2**(6), pp.828-850.10.1002/wcc.144

Prabowo, D., Maryudi, A., Senawi and Imron, M.A. 2017. Conversion of Forests into Oil Palm Plantations in West Kalimantan, Indonesia: Insights from Actors' Power and Its Dynamics. *Forest Policy and Economics.* **78**, pp.32-39.10.1016/j.forpol.2017.01.004

Prasetyo, L.B., Dharmawan, A.H., Nasdian, F.T. and Ramdhoni, S. 2016. Historical Forest Fire Occurrence Analysis in Jambi Province During the Period of 2000 – 2015: Its Distribution & Land Cover Trajectories. *Procedia Environmental Sciences.* **33**, pp.450-459.10.1016/j.proenv.2016.03.096

Prawiradilaga, D.M., Siti Purwaningsih and Irvan Susiarti. 2014. Rapid Assessment on Biodiversity in Logged Forest of Tesso Nilo Riau Province. *Jurnal Biologi Indonesia.* **10**(2), pp.271-283

Prins, E. 2001. 2 an Overview of Active Fire Detection and Monitoring Using Meteorological Satellites. In.

Purnomo, H., Shantiko, B., Sitorus, S., Gunawan, H., Achdiawan, R., Kartodihardjo, H. and Dewayani, A.A. 2017. Fire Economy and Actor Network of Forest and Land Fires in Indonesia. *Forest Policy and Economics.* **78**, pp.21-31.10.1016/j.forpol.2017.01.001

Putra, E.I., Cochrane, M.A., Saharjo, B.H., Graham, L., Thomas, A., Applegate, G., Saad, A., Setianto, E., Sutikno, S. and Prayitno, A. 2019. Developing Better Understanding on Tropical Peat Fire Occurrences and Dynamics. *IOP Conference Series: Earth and Environmental Science.* **394**, p012044.10.1088/1755-1315/394/1/012044

Pyne, S.J. 2019. *Fire a Brief History.* 2nd ed. Seattle: University of Washington Press.

Reddington, C.L., Yoshioka, M., Balasubramanian, R., Ridley, D., Toh, Y.Y., Arnold, S.R. and Spracklen, D.V. 2014. Contribution of Vegetation and Peat Fires to Particulate Air Pollution in Southeast Asia. *Environmental Research Letters.* **9**(9), p094006

Regent of Kampar. Keputusan Bupati Kampar Nomor 660-491/X/2018 Tentang Penetapan Masyarakat Hukum Adat Kenegerian Petapahan Dan Pengakuan Hutan Adat Imbo Putui. [Decree of the Kampar Regent No. 660-491 / X / 2018 Concerning the Establishment of the Kenegerian Customary Law Community and the Recognition Imbo Putui Customary Forest]. Available from: https://www.aman.or.id/wp-content/uploads/2019/06/Imbo-Putui.pdf

Regent of Kampar. 2019a. *Keputusan Bupati Kampar Nomor 660-325 Tahun 2019 Tentang Pengakuan Masyarakat Hukum Adat Dan Hak Tanah Ulayat Persukuan Petopang*. Available from: https://www.aman.or.id/wp-content/uploads/2019/06/HA-KUOK.pdf

Regent of Kampar. Keputusan Bupati Kampar Nomor 660-326 Tahun 2019 Tentang Pengakuan Masyarakat Hukum Adat Dan Hak Tanah Ulayat Kenegerian Aur Kuning. [Decree of the Kampar Regent No 660-326 Tahun

2019 concerning the Establishment of Customary Law Communities and Land Rights in Kenegerian Aur Kuning]. Available from: https://www.aman.or.id/wp-content/uploads/2019/06/HA-AUR-KUNING.pdf

Regent of Kampar. Keputusan Bupati Kampar Nomor 660-327 Tahun 2019 Tentang Pengakuan Masyarakat Hukum Adat Dan Hak Tanah Ulayat Kenegerian Terusan. [Decree of the Kampar Regent No. 660-327 / X / 2019 Concerning the Recognition of Customary Law Community and Customary Forest of the Kenegerian Terusan]. Available from: https://www.aman.or.id/wp-content/uploads/2019/06/HA-TERUSAN.pdf

Regional Goverment of Riau Province. 2020. *Informasi Umum.* [Online]. Available from: https://www.riau.go.id/home/content/61/data-umum

Rijal, S., Saleh, M.B., Jaya, I.N.S. and Tiryana, T. 2016. *Deforestation Profile of Regency Level in Sumatra.*

Robinson, J.M. 1991a. Fire from Space: Global Fire Evaluation Using Infrared Remote Sensing. *International Journal of Remote Sensing.* **12**(1), pp.3-24.10.1080/01431169108929628

Robinson, J.M. 1991b. *Problems in Global Fire Evaluation: Is Remote Sensing the Solution?* United States: Massachusetts Inst of Tech Press.

Roy, D., Giglio, L., Kendall, J. and Justice, C. 1999. Multi-Temporal Active-Fire Based Burn Scar Detection Algorithm. *International Journal of Remote Sensing.* **20**.10.1080/014311699213073

Saatchi, S.S., Harris, N.L., Brown, S., Lefsky, M., Mitchard, E.T.A., Salas, W., Zutta, B.R., Buermann, W., Lewis, S.L., Hagen, S., Petrova, S., White, L., Silman, M. and Morel, A. 2011. Benchmark Map of Forest Carbon Stocks in Tropical Regions across Three Continents. *Proceedings of the National Academy of Sciences.* **108**(24), p9899.10.1073/pnas.1019576108

Saharjo, B.H. 1997. Fire Protection and Industrial Plantation Management in the Tropics. *The Commonwealth Forestry Review.* **76**(3), pp.203-206

Schoene, D., Killmann, W., von Lüpke, H. and Loychewilkie, M. 2007. *Definitional Issues Related to Reducing Emissions from Deforestation in Developing Countries.*

Scholes, R.J., Kendall, J. and Justice, C.O. 1996. The Quantity of Biomass Burned in Southern Africa. *Journal of Geophysical Research: Atmospheres.* **101**(D19), pp.23667-23676.https://doi.org/10.1029/96JD01623

Scott, A.C., Bowman, D.M.J.S., Bond, W.J., Pyne, S.J. and Alexander, M.E. 2014. *Fire on Earth : An Introduction.* Hoboken, UNITED KINGDOM: John Wiley & Sons, Incorporated.

Setiawan, E.N., Maryudi, A., Purwanto, R.H. and Lele, G. 2016. Opposing Interests in the Legalization of Non-Procedural Forest Conversion to Oil Palm in Central Kalimantan, Indonesia. *Land Use Policy.* **58**, pp.472-481.10.1016/j.landusepol.2016.08.003

Simard, S.J. 1991. Fire Severity, Changing Scales, and How Things Hang Together. *International Journal of Wildland Fire.* **1**(1), pp.23-34

Sloan, S., Locatelli, B., Wooster, M.J. and Gaveau, D.L.A. 2017. Fire Activity in Borneo Driven by Industrial Land Conversion and Drought During El Niño Periods, 1982–2010. *Global Environmental Change.* **47**, pp.95-109.https://doi.org/10.1016/j.gloenvcha.2017.10.001

Sohlberg, R., Descloitres, J. and Bobbe, T. 2001. Modis Land Rapid Response Operational Use of Terra Data for Usfs Wildfire Management. *The Earth Observer.* [Online]. **13(5)**, pp.8 –14. Available from: https://eospso.nasa.gov/sites/default/files/eo_pdfs/Sept_Oct01.pdf

Song, X.-P., Hansen, M.C., Stehman, S.V., Potapov, P.V., Tyukavina, A., Vermote, E.F. and Townshend, J.R. 2018. Global Land Change from 1982 to 2016. *Nature.* **560**(7720), pp.639-643.10.1038/s41586-018-0411-9

Stockwell, C.E., Jayarathne, T., Cochrane, M.A., Ryan, K.C., Putra, E.I., Saharjo, B.H., Nurhayati, A.D., Albar, I., Blake, D.R., Simpson, I.J., Stone, E.A. and Yokelson, R.J. 2016. Field Measurements of Trace Gases and Aerosols Emitted by Peat Fires in Central Kalimantan, Indonesia, During the 2015 El Niño. *Atmos. Chem. Phys.* **16**(18), pp.11711-11732.10.5194/acp-16-11711-2016

Suprapto, S., Awang, S.A., Maryudi, A. and Wardhana, W. 2018. Kontestasi Aktor Dalam Proses Revisi Rencana Tata Ruang Provinsi (Rtrwp) Di Indonesia (Studi Kasus: Revisi Rtrw Provinsi Riau). *Jurnal Wilayah dan Lingkungan.* **6**(3).10.14710/jwl.6.3.193-214

Suyanto, Applegate, G., Permana, R.P., Khususiyah, N. and Kurniawan, I. 2004. The Role of Fire in Changing Land Use and Livelihoods in Riau - Sumatera.Pdf. *Ecology and Society.* **9**(1), p15

Syaufina, L. 2018. Chapter 8 - Forest and Land Fires in Indonesia: Assessment and Mitigation. In: Samui, P., et al. eds. *Integrating Disaster Science and Management.* Elsevier, pp.109-121.

Taufik, M., Torfs, P.J.J.F., Uijlenhoet, R., Jones, P.D., Murdiyarso, D. and Van Lanen, H.A.J. 2017. Amplification of Wildfire Area Burnt by Hydrological Drought in the Humid Tropics. *Nature Climate Change.* **7**, p428.10.1038/nclimate3280

https://www.nature.com/articles/nclimate3280#supplementary-information

The ASEAN Secretariat. 2002. *Asean Agreement on Transboundary Haze Pollution*.

TNNP. 2019. *Tentang Tn Tesso Nilo.* [Online]. Available from: https://tntessonilo.com/tentang-tn-tesso-nilo/

Tonoto, P. 2011. Analysis of Forest and Land Fires in Riau Province Based on the Use of Land for Mitigation of Smoke Disaster Analysis. In:

International Conference of Indonesian Forestry Researchers (INAFOR), *Bogor*.

Tonoto, P., Ishihara, M.I., Firdaus, R. and Nakagoshi, N. 2017. Peatland Fires in Riau, Indonesia, in Relation to Land Cover Type, Land Management, Landholder, and Spatial Management. *Journal of Environmental Protection.* **08**(11), pp.1312-1332.10.4236/jep.2017.811081

Torero, J.L. 2013. An Introduction to Combustion in Organic Materials. *Fire Phenomena and the Earth System.* pp.1-13.doi:10.1002/9781118529539.ch1

10.1002/9781118529539.ch1

Trimble, M. and van Aarde, R. 2012. Geographical and Taxonomic Biases in Research on Biodiversity in Human-Modified Landscapes. *Ecosphere.* **3**, part119.10.1890/ES12-00299.1

TWB. 2016. *The Cost of Fire: An Economic Analysis of Indonesia's 2015 Fire Crisis;.* Jakarta: The World Bank.

Usup, A., Hashimoto, Y., Takahashi, H. and Hayasaka, H. 2004. Combustion and Thermal Characteristic of Peat Fire in Tropical Peatland in Central Kalimantan, Indonesia. *Tropics.* **14**, pp.1-19.10.3759/tropics.14.1

van der Werf, G.R., Dempewolf, J., Trigg, S.N., Randerson, J.T., Kasibhatla, P.S., Giglio, L., Murdiyarso, D., Peters, W., Morton, D.C., Collatz, G.J., Dolman, A.J. and DeFries, R.S. 2008. Climate Regulation of Fire Emissions and Deforestation in Equatorial Asia. *Proc Natl Acad Sci U S A.* **105**(51), pp.20350-20355.10.1073/pnas.0803375105

van der Werf, G.R., Randerson, J.T., Collatz, G.J. and Giglio, L. 2003. Carbon Emissions from Fires in Tropical and Subtropical Ecosystems. *Global Change Biology.* **9**(4), pp.547-562.10.1046/j.1365-2486.2003.00604.x

Vayda, A.P. 2006. Causal Explanation of Indonesian Forest Fires: Concepts, Applications, and Research Priorities. *Human Ecology.* **34**(5), pp.615-635

Vetrita, Y. and Cochrane, M.A. 2020. Fire Frequency and Related Land-Use and Land-Cover Changes in Indonesia's Peatlands. *Remote Sensing.* **12**(1).10.3390/rs12010005

Wahyunto, Nugroho, K. and Agus, F. 2016. Perkembangan Pemetaan Dan Distribusi Lahan Gambut Di Indonesia. In: Agus, F., et al. eds. *Lahan Gambut Indonesia - Pembentukan Karakteristik Dan Potensi Mendukung Ketahanan Pangan.* 2 ed. Jakarta: IAARD Press, p.41.

Wahyunto, Nugroho, K., Ritun, S. and Sulaeman, Y. 2014. *Indonesian Peatland Map - Method, Certainty and Uses.* Indonesian Center for Agricultural Land Resources Research and Development.

Wooster, M., Roberts, G., Smith, A., Johnston, J., Freeborn, P., Amici, S. and Hudak, A.T. 2013. Thermal Remote Sensing of Active Vegetation Fires and Biomass Burning Events. pp.347-390.

WWF. 2015. *Saving Forests at Risk.* WWF.

WWF Indonesia. *Conservation Planning.* [Online]. [Accessed 21 June 2020]. Available from: https://www.wwf.or.id/en/about_wwf/whatwedo/forest_species/where_we_work/tessonilobukittigapuluh/whoweare/conservationplanning/

Yeager, C., Marshall, A., Stickler, C. and Chapman, C. 2003. Effects of Forest Fires on Peat Swamp and Lowland Dipterocarp Forests in Kalimantan, Indonesia. *Tropical Biodiversity.* **8**, pp.121–138

Chapter 3

Relationship Between Fire and Forest Cover Loss in Riau Province, Indonesia Between 2001 and 2012

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Abstract: Forest and peatland fires occur regularly across Indonesia, resulting in large greenhouse gas emissions and causing major air quality issues. Over the last few decades, Indonesia has also experienced extensive forest loss and conversion of natural forest to oil palm and timber plantations. Here we used data on fire hotspots and tree-cover loss, as well as information on the extent of peat land, protected areas, and concessions to explore spatial and temporal relationships among forest, forest loss, and fire frequency. We focus on the Riau Province in Central Sumatra, one of the most active regions of fire in Indonesia. We find strong relationships between forest loss and fire at the local scale. Regions with forest loss experienced six times as many fire hotspots compared to regions with no forest loss. Forest loss and maximum fire frequency occurred within the same year, or one year apart, in 70% of the 1 km^2 cells experiencing both forest loss and fire. Frequency of fire was lower both before and after forest loss, suggesting that most fire is associated with the forest loss process. On peat soils, fire frequency was a factor 10 to 100 lower in protected areas and natural forest logging concessions compared to oil palm and wood fiber (timber) concessions. Efforts to reduce fire need to address the underlying role of land-use and land-cover change in the occurrence of fire. Increased support for protected areas and natural forest logging concessions and restoration of degraded peatlands may reduce future fire risk. During times of high fire risk, fire suppression resources should be targeted to regions that are experiencing recent forest loss, as these regions are most likely to experience fire.

Keywords: Forest cover loss; Fire Hotspot; Riau Province Indonesia

3.1 Introduction

Forest and peatland fires occur annually across Indonesia, resulting in large greenhouse gas emissions (Page et al., 2002) and causing major regional air quality issues (Crippa et al., 2016; Marlier et al., 2013). The occurrence of fire in Indonesia is influenced both by climate (Fanin and van der Werf, 2017; van der Werf et al., 2008) and by extensive land-cover change (Langner et al., 2007). There is an urgent need to better understand how agricultural and plantation management can be altered to minimize fire and associated environmental impacts (Meijaard and Sheil, 2019; Wijedasa et al., 2017). Here we analyze twelve years of data on the occurrence of fire and data on tree cover loss to better understand links between fire and land-cover change in Riau Province, Indonesia.

Emissions from vegetation and peat fires in Indonesia contribute to climate change and cause severe regional air quality issues (Crippa et al., 2016; Marlier et al., 2013). The large fires across Indonesia in September–October 2015, emitted 700–800 Tg CO_2 (Huijnen et al., 2016; Kiely et al., 2019), and exposed 69 million people to poor air quality (Crippa et al., 2016). Exposure to particulate pollution is estimated to have caused 11,880 mortalities in the short term (Crippa et al., 2016) with as many as 100,300 premature mortalities over the longer term (Koplitz et al., 2016). Peatland regions experiencing rapid land cover change and frequent fires in central and southern Sumatra and southwest Kalimantan contribute the most to regional air quality issues (Reddington et al., 2014).

Extensive fires in Indonesia mainly occur during dry years linked to the El Niño Southern Oscillation and the Indian Ocean Dipole (IOD) (Fanin and van der Werf, 2017), with a nonlinear sensitivity of fire to dry conditions (Field et al., 2016). However, despite the occurrence of drought years, large fire events did not occur prior to the 1960s in Sumatra and the 1980s in Kalimantan, periods when extensive land-cover change began (Field et al., 2009). Undisturbed tropical forests and peatlands are typically sufficiently wet to be resistant to fire (Cochrane and Schulze, 1999; Page et al., 2002). Deforestation and forest degradation provide abundant fuels, and drainage of peatland soils accelerates groundwater drawdown increasing the flammability of peat (Taufik et al., 2017). This demonstrates how anthropogenic land-cover change has modified the occurrence of fire across Indonesia.

Fires now occur annually across extensive regions of Indonesia, even in years without drought (Gaveau et al., 2014). Satellite studies of active fire detections (Fanin and van der Werf, 2017; Kiely et al., 2019; van der Werf et al., 2008) as well as the area burned by fire (Giglio et al., 2018) provide new information on the occurrence of fire and the relationship with climate and land-use change. Over a 10-year period, fires burned 16.2 Mha of Borneo, or 21% of the land surface (Langner and Siegert, 2009).

Over the last few decades, Indonesia has also experienced extensive forest loss and conversion of forest to oil palm and wood fiber plantations (Gaveau et al., 2016; Harris et al., 2017). Satellite remote sensing has provided new understanding of the spatial and temporal rate of forest loss (Hansen et al., 2009). Between 1973 and 2015, 14.4 Mha of primary natural forest in Borneo was cleared (Cochrane and Schulze, 1999). The rate of tree cover loss in Indonesia increased from less than 10,000 km^2 yr^{-1} in 2000–2003 to over 20 000 km^2 yr^{-1} in 2011–2012, resulting in one of the largest increments of tree cover loss rate worldwide (Hansen et al., 2013), although forest loss rates include clearance of timber plantations and oil palm estates. In total, 60,200 km^2 of primary natural forest loss occurred across Indonesia over the period 2000 to 2012, increasing by 476 km^2 yr^{-1} (Margono et al., 2014). The largest increase of primary tree cover loss occurred in wetland (peat) areas and almost all clearing of forests occurred on previously degraded land, meaning logging preceded land conversion. Forests in Indonesia contain important aboveground and below ground carbon stocks (Ekadinata and Dewi, 2011; Harja et al., 2011), meaning forest loss will alter the carbon balance in the region. Indonesia's largest single driver of deforestation in 2001–2016 was oil palm plantations, which contributed 23% of deforestation nation-wide (Austin et al., 2019). Recently, the dominant role of logging in the transformation of peat swamp forests in Southeast Asia has also been emphasized (Dohong et al., 2017).

Land-cover change is connected to fire through a multi-year processes involving road building, logging, and forest fragmentation (Cochrane, 2003; Juárez-Orozco et al., 2017). Since fire and deforestation have direct interactions, understanding the relationship between them is very important (Lavorel et al., 2006). There are four major direct causes of fires in Indonesia: fire used as a tool in land clearance; accidental or escaped fires; fire used as a weapon in land tenure or land-use disputes; and fire connected with resource extraction (Dennis et al., 2005). The same study identified five underlying causes of fire: land tenure and land use allocation conflicts and competition, forest degradation practices, economic incentives/disincentives, population growth and migration, and inadequate firefighting and management capacity

Forest fires are closely related to land cover dynamics in Indonesia. Fire activity is mostly detected in wood fiber (timber) concessions, both in Sumatra (Marlier et al., 2015b) and Kalimantan (Langner and Siegert, 2009). In Sumatra, 58% of the fires in 2013 occurred on land that had been forest five years previously (Gaveau et al., 2014). In Riau, more than 90% of the area of severely burnt primary vegetation eventually changed land cover type over the period 1998–2002 (Miettinen and Liew, 2005). At a study site in Riau Province, fire was used as a tool for land preparation by oil palm companies, industrial timber plantation, and smallholders, with crop planting often occurring shortly after burning, suggesting a link between fire and land-use change (Suyanto et al., 2004). Albar (2015) found that 72% of fire hotspots in Riau Province during 2006 to 2013 occurred within non-forest areas, with the number of fire hotspots increasing over this period. Comparing land-use and land-cover between one year before and three years after fire occurrences in Jambi, a province adjacent to Riau, shows that 20% of the area burned by fires became forest plantation, 27% became oil plantation and 52% was converted into small holder/community land area (Prasetyo et al., 2016). In Kalimantan, enhanced fire frequency occurs within 10 km of oil palm, with oil palm extent associated with increased fire frequency until covering 20% of an area (Sloan et al., 2017).

Although these studies demonstrate that fire and land-cover change are closely linked, there is still limited information on the spatial and temporal relationship between fire and land-cover change for peatland regions of Indonesia. Specifically, there have been no detailed studies of how tree cover loss and fire frequency are related spatially and temporally across different land-cover and land-use types. We focus our analysis on hotspot dynamics related to tree cover loss for peat and mineral soils with a range of land-use types in Riau province, Sumatra, one of the most active fire regions in Indonesia. Our aim is to explore the spatial and temporal connections between fire and tree cover loss, providing new information to help forest management, peat restoration, and fire suppression efforts.

3.2 Materials and Methods

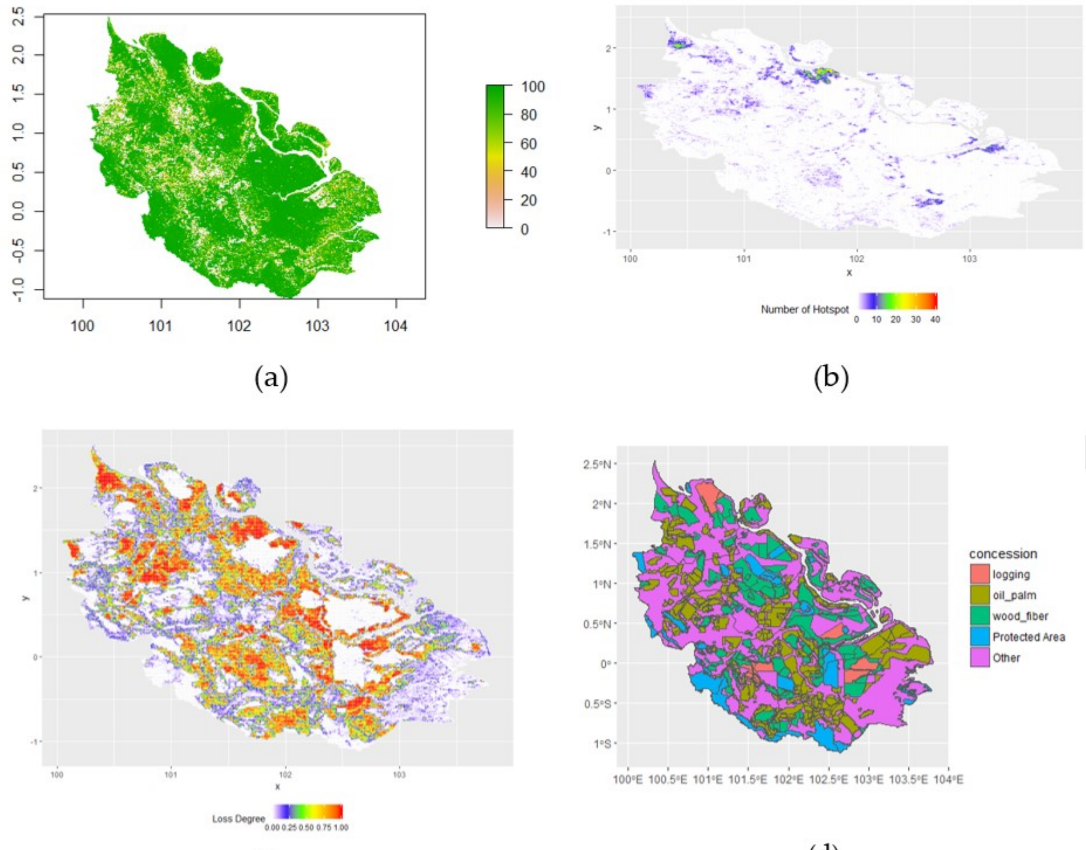
Our study area is Riau Province, Indonesia, situated in central eastern coast of Sumatra Island, facing the Strait of Malacca and adjacent to Singapore and Malaysia. Riau covers a geographic area of 89 691 km2 extending between 100°00' – 105°05' E and 01°05' and 02°25' S. In the early 1970s, Riau was still covered with extensive forest areas with over 95% of the province classified as state forest area at that time (Ministry of Forestry of the Republic of Indonesia 1986). Since the 1970s, Riau has experienced rapid expansion of plantation forestry. Agriculture (including forestry) is now a very important sector in this province, contributing approximately 20% of Gross Regional Domestic Product and accounting for 46% of the workforce. Oil palm plantations are important for development as they may decrease poverty in rural areas (Bappenas, 2015), providing economic benefits for around 2.6 million Indonesians (Edwards, 2019).

We used data on fire hotspots and tree-cover loss, as well as information on the extent of peat land, protected areas, and concession areas of wood fiber, logging, and oil palm plantation (Figure 3.1). Peatland, concession area, and protected area extents in 2010 are from the World Resources Institute and accessed through Global Forest Watch (http://data.globalforestwatch.org/datasets).

Concessions include oil palm, wood fiber, and logging concessions. Oil palm concessions are used for industrial-scale oil palm plantations. Wood fiber concessions are used for plantations of fast-growing tree species for wood pulp and paper production. Logging concessions are natural forest areas used for selective timber extraction (Marlier et al., 2015b). Regions outside concessions and protected areas, are defined as “Other”. This “Other” land use is stated as a non-forest area (Area Penggunaan Lain / APL) by the Ministry of Forestry (Regulation No 50 Year 2009) such as agriculture, transmigration and mining.

To study the effect of fire on land cover, such as in tropical deforestation (Lambin and Ehrlich, 1997), information on when and where fires burn is more useful than the exact area burnt. Active fire detection instruments are important in determining fire seasonality, timing, and interannual variations (Eva and Lambin, 1998). Information on the timing and location of fires was obtained from Moderate Resolution Imaging Spectro-radiometer (MODIS, NASA, USA) MCD14ML Global Monthly Fire Location Product Collection 6, which contains the geographic coordinates of individual active fire hotspots.

Hotspot pixels are detected by the MODIS instrument on Terra and Aqua satellites. The Terra satellite passes the same region of Earth every 1–2 days at approximately 10:30 A.M. local time, while Aqua overpasses at 1:30 P.M. local time. The restricted satellite overpass time may result in missed fire detections due to cloud cover or fire occurring when the satellites are not overhead. For example, morning or evening fires will remain undetected.



(a) (b)

(c) (d)

Figure 3.1 Land-cover and land-use in Riau Province, Sumatra, Indonesia. (a) Percentage canopy cover in year 2000; (b) Total number of high confidence fire hotspots detected between 2001 and 2012; (c) Fractional tree cover loss between 2001 and 2012; (d) Concession

The MODIS instrument has 36 bands with three spatial resolutions: 250 m (bands 1–2), 500 m (bands 3–7), 1000 m (bands 8–36). Fire pixels are detected based on the radiation emission of T4 mid-infrared (band 21 and 22) and T11 far-infrared (band 31) channels. Therefore, the spatial resolution of MODIS hotspots is 1 km. Other attributes include acquisition time, confidence level, and fire radiative power (FRP). The ranges for confidence class of fire pixel are low (0–30), nominal (30–80), or high (80–100) (Giglio, 2010). Previous work found a high commission error in areas of low fire activity (Hantson et al., 2013), so we restrict our analysis to high confidence hotspots. The hotspot dataset is downloaded from https://firms.modaps.eosdis.nasa.gov/download/ and then subsequent analysis completed using R.

For information on tree cover loss we use the Global Forest Change (GFC) dataset (Chisholm et al., 2015) derived from band 3, 4, 5, and 7 of Landsat 7 Enhanced Thematic Mapper Plus (ETM+) images, with 30 m resolution. We use the Hansen_GFC-2017-v1.5 dataset, which contains information on tree canopy cover for year 2000 (treecover2000) and year of gross forest cover loss over the period 2000–2017 (lossyear). Tree cover loss over 2000 to 2017 period has not been produced in a consistent way, so we restrict our analysis to 2000 to 2012, when a consistent analysis of forest loss is available. Data was downloaded from https://earthenginepartners.appspot.com/science-2013-global-forest/download_v1.5.html. GFC defines trees as all vegetation taller than 5 m in height. Forest loss occurs when tree cover declines to < 50%, and includes loss of forest as a result of fire. Forest loss includes clearance of plantations and oil palm estates as well as loss of natural forest.

3.3 Results

3.3.1 Summary of fire hotspot frequency and tree cover loss

Table 3.1 summarises fire hotspot frequency and tree cover loss in Riau Province between 2001 and 2012. Over that period, there were 44043 high confidence hotspots and 33334 km^2 of tree cover loss, accounting for 37% of the province. In the year 2000, 88% of Riau was covered with forest (defined as tree cover ≥ 50%) with 42% of this forest lost between 2001 and 2012. On average, there are 0.49 hotspot km^{-2}, or 1.32 hotspots per km^2 of tree cover loss. Over the 2001 to 2012 period, 58% of 1 km^2 cells experienced tree loss greater than 10% and 18% of cells experienced at least one fire hotspot.

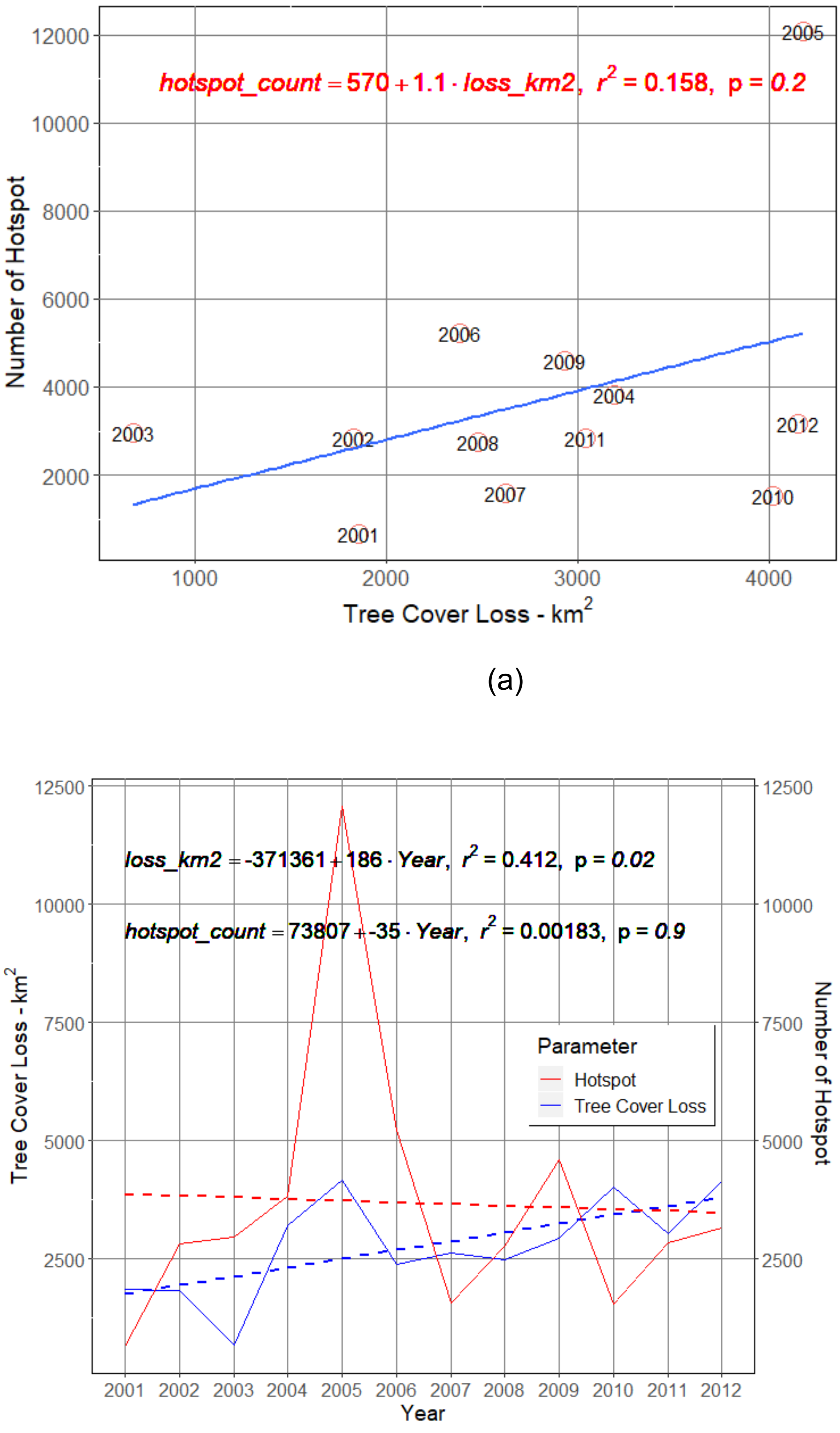
Table 3.1 Annual forest loss and hotspot density in peat and non-peatland areas.

Land Type	**Area (km^2)**	**Loss (km^2)**	**Hotspot Count**	**Loss Proportion**	**Hotspot Density (km^{-2})**	**Hotspot Density per Loss (km^{-2})**	**Annual Loss Proportion (yr^{-1})**	**Annual Hotspot Density (km^{-2} yr^{-1})**	**Cells with Hotspot**	**Cells with Loss > 10%**
a	b	c	d	e = c/b	f =d/b	g = d/c	h = e/12	i = f/12	j	k
Non-Peat	51492	16625	14006	0.32	0.27	0.84	0.027	0.02	7991	30178
Peat	38639	16709	30037	0.43	0.78	1.80	0.036	0.06	8592	23633
All Land Type	Σ= 90131	Σ= 33334	Σ= 44043	Π = sum(c) / sum(b) = 0.37	Π = sum(d)/ sum(b) = 0.49	Π = sum(d)/ sum(c) = 1.32	Π = 0.031	Π = 0.041	Σ= 16583	Σ=53811

Table 3.1 also gives the fire hotspot frequency and tree cover loss for peatland and non-peatland areas. Riau consists of 57% non-peatland and 43% peatland areas. Both peatland and non-peatland areas experienced a similar area tree cover loss of around 16 500 km^2, accounting for 43% of peatland and 32% of non-peatland areas. Hotspot density is a factor of three greater on peatlands compared to non-peatlands, being on average 0.06 km^{-2} yr^{-1} in peatland areas and 0.02 km^{-2} yr^{-1} in non-peatlands.

3.3.2 The relationship between annual rates of forest loss and annual number of fire hotspots

Figure 3.2 shows the relationship between annual rates of forest loss and annual number of fire hotspots between 2001 and 2012 across Riau. Both tree cover loss and the number of fire hotspots were greatest in 2005. The correlation between total annual number of hotspots and annual rate of tree cover loss is not significant at the provincial level (Figure 3.2a,r^2 =0.158). Over the period 2001 to 2012, there was an insignificant change in the annual number of fire hotspots (−35 hotspots yr^{-1}), whilst the rate of tree cover loss increased significantly ($p<0.05$) by 186 km^2 yr^{-1} (Figure 3.2b). The increase in forest loss rate despite no increase in fire may be partly due to large companies transitioning from using fire to using mechanical methods to clear land (Chisholm et al., 2015). We explore this possibility in more detail later in the paper.



(a)

(b)

Figure 3.2 (a) Relationship between annual number of hotspots and tree cover loss in Riau Province; (b) Annual tree cover loss and number of hotspots Annual tree cover loss (blue lines, left axis) and number of fire hotspots (red lines, right axis) in Riau. The solid lines represent actual number and the dashed lines show the estimated linear trend lines. The equation of best fit line ad the correlation coefficient (r^2) is shown.

3.3.3 The relations between annual hotspot density and tree cover loss

Figure 3.3 shows hotspot density as a function of tree cover in the year 2000 and tree cover loss (2000 to 2012). In both peat and non-peat regions, annual hotspot densities are relatively low in intact areas with high fractional tree cover in 2000 and low fractional tree cover loss as well as in heavily developed areas with low tree cover in 2000. Highest hotspot densities are found in regions which lost all their tree cover, either areas with high tree cover in 2000 and high fractional loss or regions with intermediate tree cover in 2000 and intermediate tree cover loss.

Table 3.2 shows average hot spot densities for regions categorised by their tree cover in 2000 and by the fractional tree cover loss over the period 2000 to 2012. We found the hotspot density to be 0.042 km^{-2} yr^{-1} in regions with forest cover in the year 2000 (>50% canopy cover in year 2000) compared to 0.023 km^{-2} yr^{-1} in regions with no forest cover in the year 2000. The hotspot density in regions of forest loss (>10% loss) was 0.138 km^{-2} yr^{-1}, a factor 6.5 greater than the hotspot density of 0.021 km^{-2} yr^{-1} in regions with no forest loss.

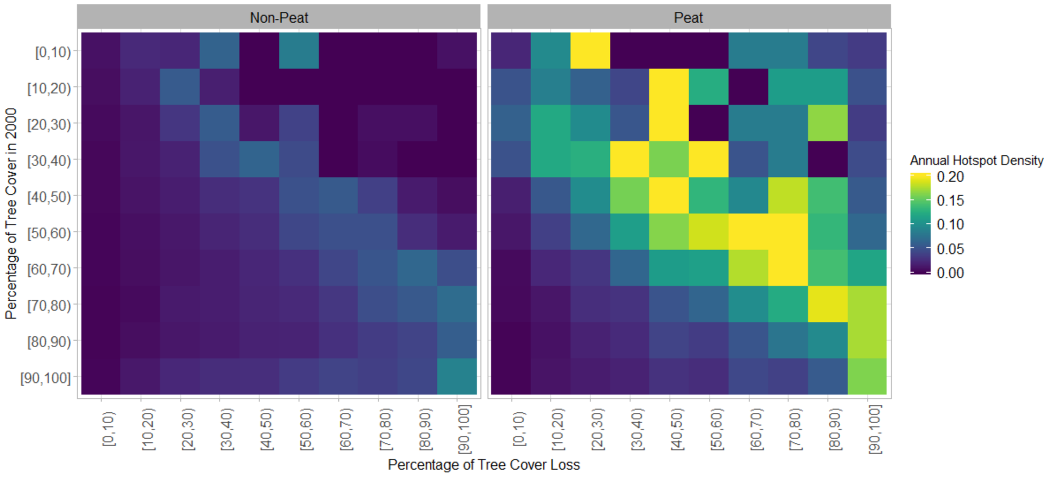


Figure 3.3 Annual hotspot density (km^{-2}yr^{-1}) as a function of percentage of tree cover loss (2000 to 2012) and percentage tree cover in the year 2000. Results are shown separately for non-peat and peat regions.

Table 3.2 Annual hotspot density by loss status[1].

Loss Status	Forest Status	Number Cells	Hotspot Total	Hotspot Density (km^{-2})	Annual Hotspot Density (km^{-2} yr^{-1})
a	b	c	D	e = d/c	f = e/12
All	Forest	79844	40533	0.51	0.042
All	Non forest	12656	3510	0.28	0.023
Loss	All	14902	24663	1.65	0.138
No loss	All	77598	19380	0.25	0.021
Loss	Forest	14654	24554	1.68	0.14
Loss	Non forest	248	109	0.44	0.037
No loss	Forest	65190	15979	0.25	0.021

[1] Forest if tree cover in 2000 > 50%, Loss if tree cover loss > 10%.

3.3.4 Fire hotspot frequency and tree cover loss in the different land-use types

Figure 3.4 shows these results separately for peat and non-peat areas. Peatland areas experienced higher hotspot density than non-peat areas in all forest and loss status categories. In forested peatland areas, regions with tree cover loss experienced 8 times more fire hotspots that regions without tree cover loss.

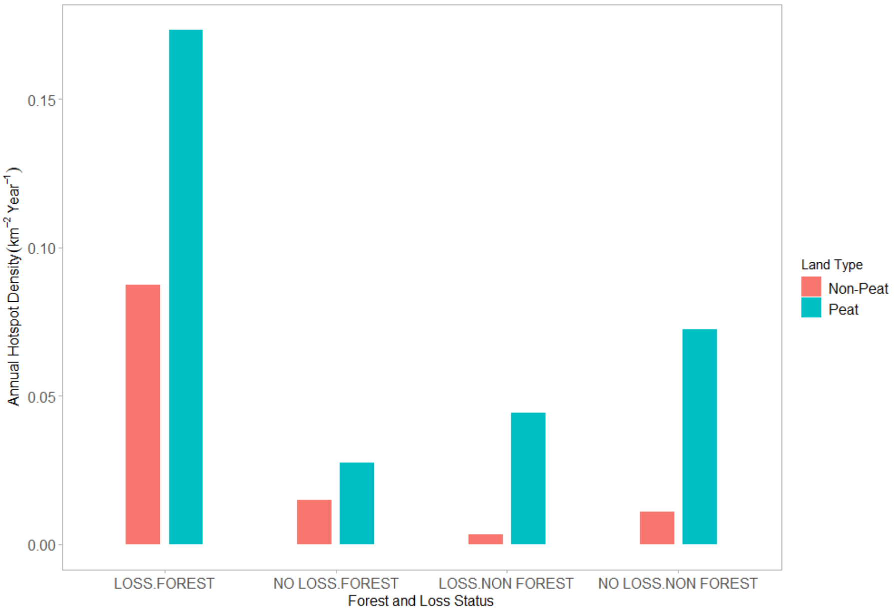


Figure 3.4 Annual hotspot density according to forest cover and forest loss status. Forest is defined as areas which have a tree cover in 2000 > 50%; areas of forest loss are defined as areas with tree cover loss > 10%.

3.3.5 Fire hotspot frequency and tree cover loss for the different land-use types

Table 3.3 shows fire hotspot frequency and tree cover loss for the different land-use types. Wood fiber concession areas had the highest proportional forest loss (5.8% yr^{-1}) and hotspot density (0.06 km^{-2} yr^{-1}). Previous studies have also found that fire was greatest in wood fiber concessions in Sumatra (Marlier et al., 2015a). Protected areas experienced the lowest proportional forest loss rate (1% yr^{-1}) and hotspot density (0.018 km^{-2} yr^{-1}). We calculate that the average forest loss rate in oil palm plantations in Riau was 2.8% yr^{-1}, less than the mean rate of 7.5% yr^{-1} in oil palm plantations across Sumatra (Carlson et al., 2017). Further analysis is required to understand whether this discrepancy is due to a different oil palm plantation development stage between Riau and another regions in Sumatra (Cattau et al., 2016a; Pramudya et al., 2018). As reported previously (Marlier et al., 2015b), areas outside protected areas and concessions, here categorized as “Other”, experienced similar rates of proportional forest loss (2.6% yr^{-1}) and hotspot density (0.038 km^{-2} yr^{-1}) compared to concessions.

Table 3.3 Annual forest loss and hotspot density as a function of land-use.

Land Use	Area (km^2)	Loss (km^2)	Hotspot Count	Loss Proportion	Hotspot Density (km^{-2})	Hotspot Density per Loss (km^{-2})	Annual Loss Proportion ($Year^{-1}$)	Annual Hotspot Density (km^{-2} $Year^{-1}$)
a	b	c	d	e = c/b	f = d/b	g=d/c	h = e/12	i = f/12
Logging	2860	864	737	0.3	0.26	0.85	0.025	0.022
Oil palm	20266	6987	10502	0.34	0.52	1.50	0.028	0.042
Other	42745	13213	19334	0.31	0.45	1.46	0.026	0.038
Protected	7920	1065	1740	0.13	0.22	1.63	0.011	0.018
Wood Fiber	16340	11205	11730	0.69	0.72	1.05	0.058	0.06

3.3.6 Fire dynamics based on both land-use and land type

To explore relationships between fire hotspots and tree cover loss, we analyzed the fire dynamics based on both land-use and land type (peatland or non-peatland). Figure 3.5 shows the area of each land-use type in Riau, separately shown for peatland and non-peatland areas. Non-peatland areas are dominated by “other” (51%) and oil palm (25%), whereas peatlands are dominated by “other” (43%), wood fiber (27%) and oil palm (19%). In both peatlands and non-peatlands, the smallest areas was taken by logging concessions.

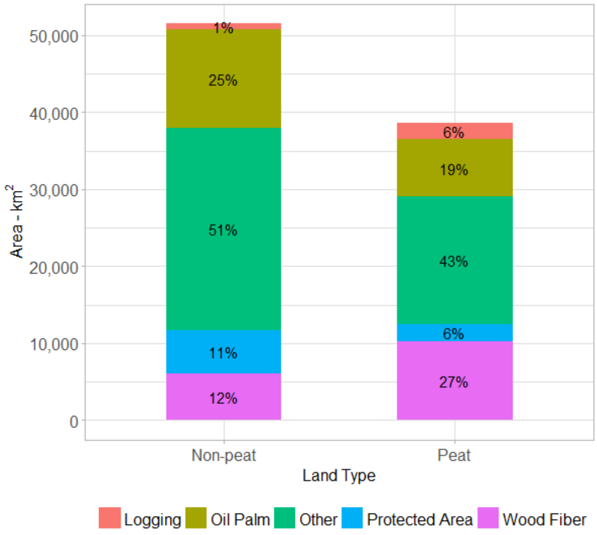


Figure 3.5 Area by land-use in peat and non-peat regions

Since “other” areas cover the majority of the region, then, not surprisingly, these also suffered the largest extent of tree cover loss, accounting for 40% of provincial forest loss (Figure 3.6). Although wood fiber concessions only accounted for 11% of land area in non-peatlands and 27 % in peatland area, they had 26% and 41% of tree cover loss, respectively. In contrast, protected areas accounted for 11% of non-peatland areas and 6% of peatland areas experienced only 5.8% and 0.6% of the tree cover loss, respectively.

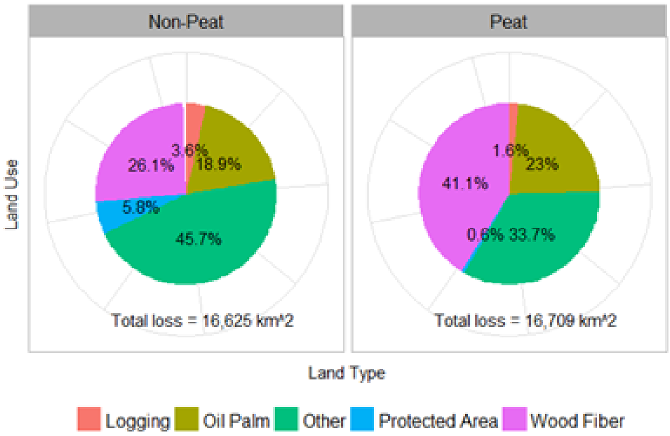


Figure 3.6 The proportion of tree cover loss by land-use in peat and non-peat regions

In peatland areas, the majority of hotspots occurred on “other”, wood fiber, and oil palm concession, with very few hotspots in protected areas or logging concessions (Figure 3.7). In non-peatland areas, hotspots occurred mostly in “other” land use (44%), with 27% in wood fiber, 24% in oil palm, 4% in protected area, and 1 % in logging concession area.

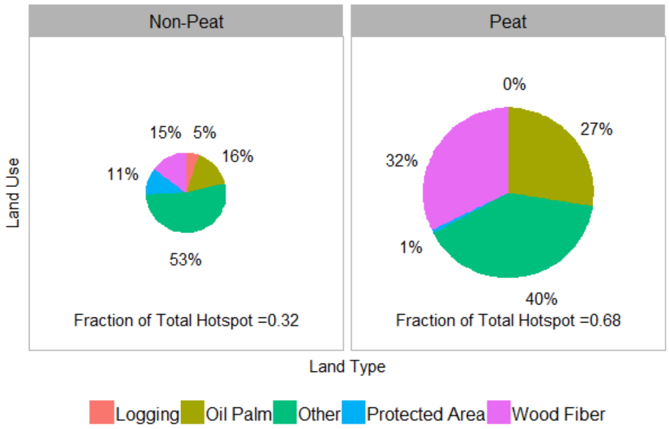


Figure 3.7 Proportion of hotspot number by land-use in peat and non-peat regions

3.3.7 Comparison of forest loss rates and hotspot density across different land-uses.

Figure 3.8 illustrates hotspot density and fractional tree cover loss within each land-use type separately for peatland and non-peatland areas (Table 3.4). The greatest fractional forest loss occurred in logging concessions in non-peatland areas (81%) and in wood fiber concessions in both peatland (67%) and non-peatland (71%) areas. Oil palm concessions experienced 25% forest loss in non-peatlands and 51% in peatlands. In contrast, logging concessions experienced a very high rate of tree cover loss in non-peatlands (81%), but only 13% in peatlands. Protected areas experienced the lowest fractional tree cover loss of 5% in peatlands and 17% in non-peatland areas.

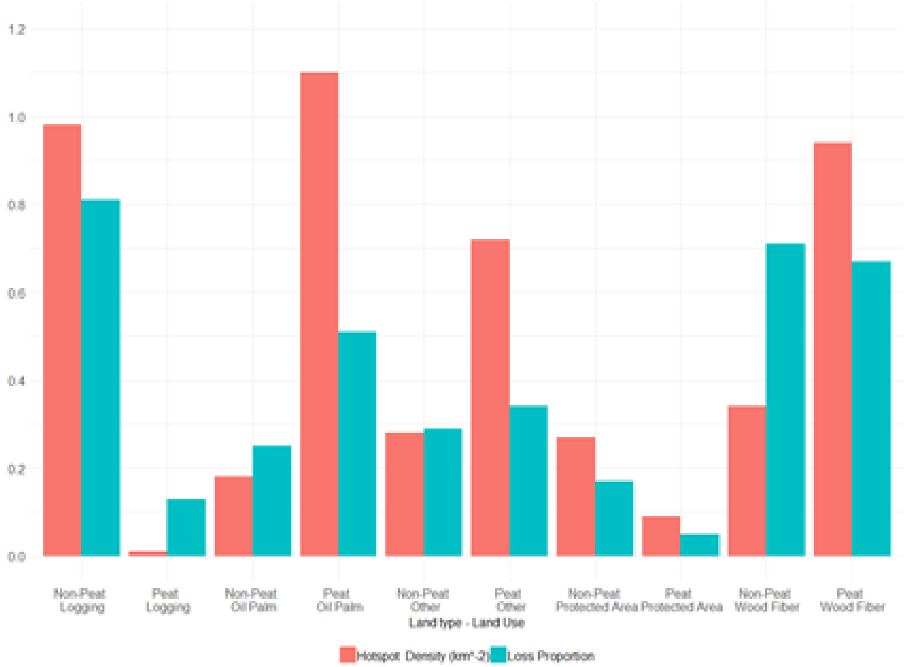


Figure 3.8 Comparison of Proportional forest loss (green) and hotspot density (red, km^{-2})

For each concession type, peatland areas had higher hotspot density compared to non-peatland areas, except for logging and protected areas, where this pattern reversed. In peatland areas, hot spot density is greatest on oil palm (0.09 km^{-2} yr^{-1}) and wood fiber (0.08 km^{-2} yr^{-1}) concessions. From 2002 to 2015, an average fire rate over oil palm plantations in Sumatra and Kalimantan of 0.078 hotspot km^{-2} yr^{-1} has been reported (Carlson et al., 2017), similar to the rate we report for oil palm on peatlands. On non-peatlands, hot spot density is greatest on logging concessions (0.08 km^{-2} yr^{-1}), but less than 0.03 km^{-2} yr^{-1} in all other land cover types. On peatlands, the lowest hotspot density is observed in logging concessions (0.0008 km^{-2} yr^{-1}) and protected areas (0.008 km^{-2} yr^{-1}), possibly due to the lack of drainage and higher forest cover in these land covers making them less susceptible to fire. Protected areas also have low hotspot density on non-peat soils (0.02 km^{-2} yr^{-1}). In peatland areas, we found that the hotspot density in oil palm and wood fiber concessions is more than a factor 100 greater than in logging concessions and a factor 10 greater than in protected areas. A previous study also found fire ignition density in Kalimantan was substantially greater in non-forest (0.06 km^{-2}) and oil palm (0.055 km^{-2}) compared to forest (0.006 km^{-2}) areas (Noojipady et al., 2017) .

Across these different land-covers, there is a significant correlation between fire hotspot density and proportional forest loss rates ($r^2 = 0.55$, $p = 0.01$, Figure 3.9). Across all land use types, stronger correlations exist for peat areas ($r^2 = 0.84$, $p = 0.03$) compared to non-peat areas ($r^2 = 0.6$, $p = 0.1$). Analyzing land-use over peatland and non-peatland separately shows that peatlands experience double the number of fire hotspots in relation to forest loss compared to non-peatland areas (see gradients of linear regressions in Figure 3.9). On non-peat areas, wood fiber concessions experience relatively little fire in relation to the rate of forest loss. On peat areas, oil palm concessions experience a lot of fire in relation to the rate of forest loss.

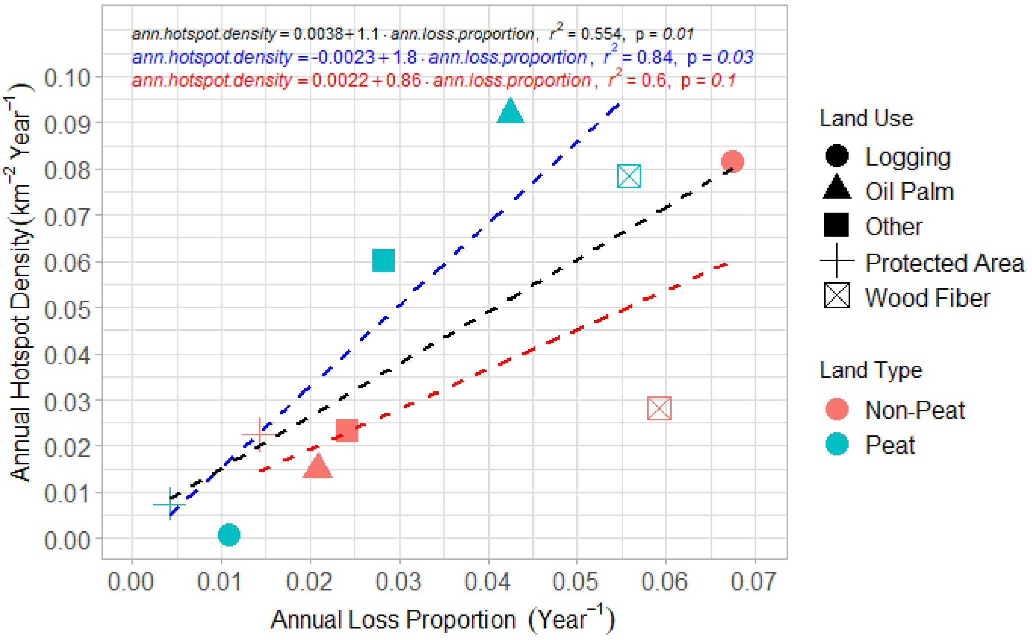


Figure 3.9.Correlation between annual proportional forest loss and annual hotspot density. Dashed lines show regression lines for peat (blue), non-peat (red) and both (black).

over loss and fire hotspot by land-use and land type[1]

Land Use	Land Type	Area (km²)	Loss (km²)	Hotspot Count	Tree Cover 2000	Loss Prop.	Loss w.r.t. 2000	Hotspot Density (km⁻² Year⁻¹)	Hotspot Density by Loss (km⁻²)	Cells with Hotspot	Cells with Loss > 10%
a	b	c	d	e	f	g	h	i	j	K	l
Logging	Non-peat	726	591	711	735	0.81	0.8	0.98	1.2	374	662
Logging	Peat	2134	273	26	2199	0.13	0.12	0.01	0.1	25	480
Oil palm	Non-peat	12769	3150	2259	10075	0.25	0.31	0.18	0.72	1386	6324
Oil palm	Peat	7497	3837	8243	6449	0.51	0.59	1.1	2.15	2478	5652
Other	Non-peat	26266	7589	7435	21172	0.29	0.36	0.28	0.98	4195	15707
Other	Peat	16479	5624	11899	16070	0.34	0.35	0.72	2.12	3464	9182
Protected Area	Non-peat	5652	960	1534	5468	0.17	0.18	0.27	1.6	799	1717
Protected Area	Peat	2268	105	206	2276	0.05	0.05	0.09	1.97	92	227
Wood fiber	Non-peat	6080	4335	2067	5348	0.71	0.81	0.34	0.48	1237	5768
Wood fiber	Peat	10260	6870	9663	10052	0.67	0.68	0.94	1.41	2533	8092
	Summary	Σ= 90131	Σ= 33334	Σ= 44043	Σ= 79844	Π = sum (d) / sum(c) = 0.37	Π = 0.425	Π = sum(e) / sum(c) = 0.49	Π = sum(e) /sum(d) = 1.32	*n*= 16583	*n*= 53811

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[1] Column g shows loss proportion for each area types (e/d), hotspot densities show hotspot number per km2 related to of area (i = e/c) and loss area (j = e/d). Treecover2000 is number of 1 km2 cells with percentage of tree cover > 50% in year 2000

3.3.8 The relationship between annual forest loss and number of hotspots within each land-use type.

Figure 3.10 shows the relationship between annual forest loss and number of hotspots within each land-use type. Relationships between annual forest loss and annual number of hotspots are generally positive. Logging concessions and protected areas exhibit strong correlations ($r^2 > 0.45$) between annual forest loss and fire in both peat and non-peat areas. In contrast, relationships in wood fiber and oil palm concessions are weak ($r^2 < 0.2$) in both peat and non-peat areas. Across all land-use types, correlations are stronger in peatland compared to non-peatland areas.

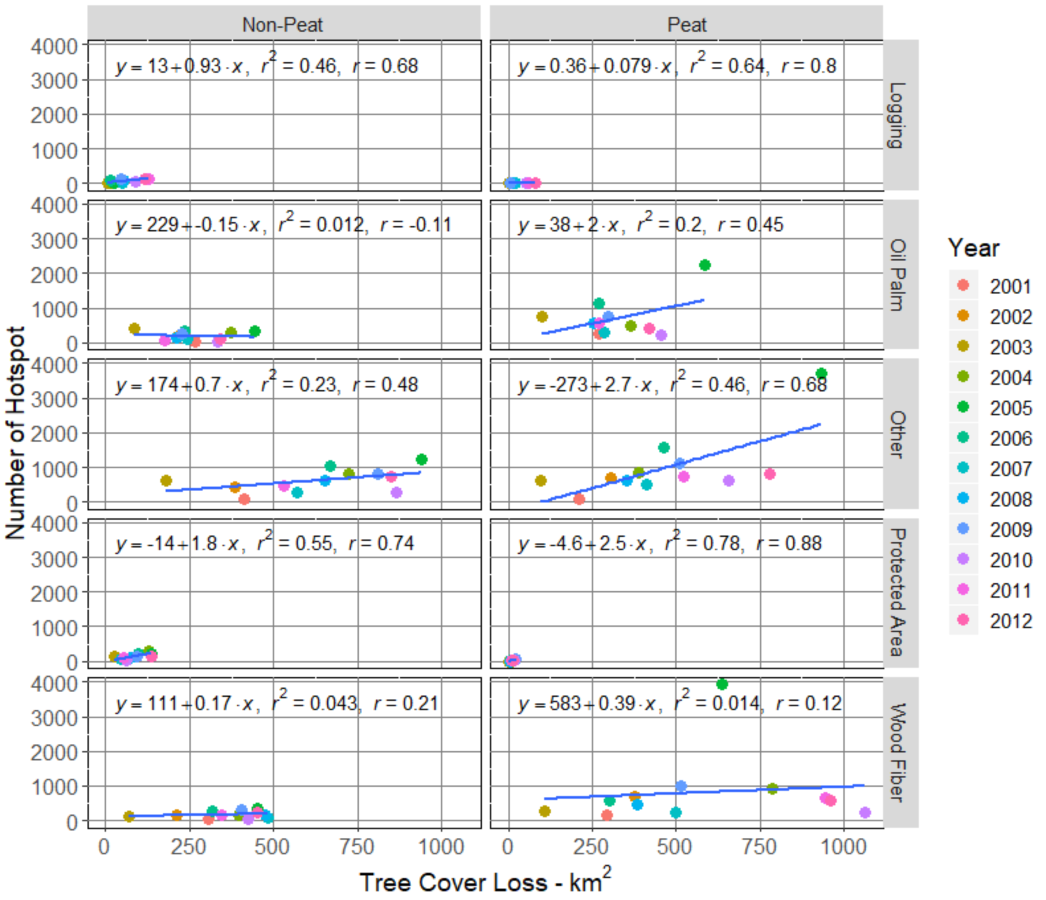

Figure 3.10 Relationship between tree cover loss and number of hotspots by land type and land use.

Figure 3.11 shows the rate of change of annual number of fire hotspots and annual tree cover loss over the period 2001 to 2012 for different concession types in peatland and non-peat regions. The rate of tree cover loss increased in all areas, but particularly in wood fiber concessions and Other, which account for 40% and 43% of the province-wide increment in tree cover loss. Fire shows different behavior, with little significant change in the number of fire hotspots. On peatlands, oil palm and wood fiber concessions exhibit non-significant declines in the number of fire hotspots.

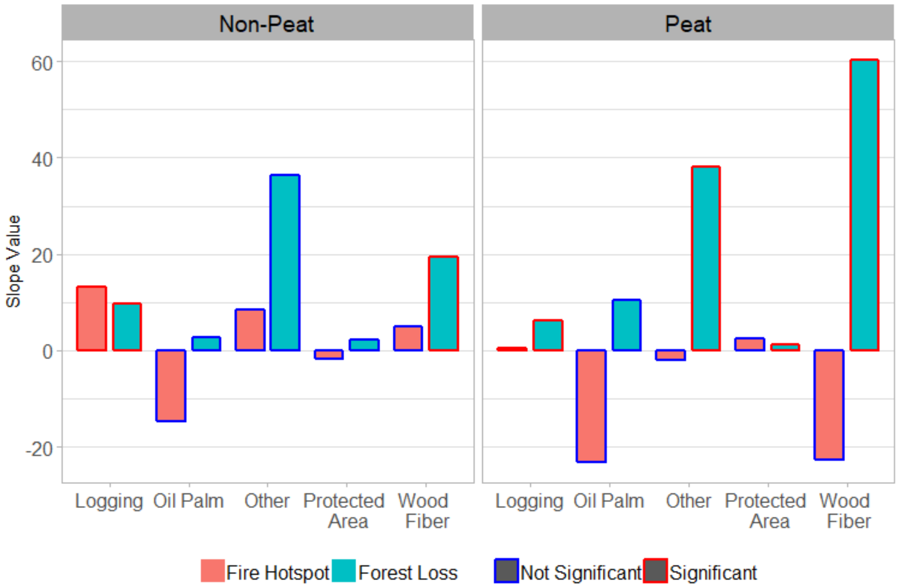

Figure 3.11 Annual increment in the number of fire hotspots (yr^{-1}) and the rate of forest loss (km^2 yr^{-1}) in non-peat and peat regions.

3.3.9 The relationships between tree cover loss and hotspots at the local scale.

In Table 3.5 Occurrence of hotspots in 1 km^2 cells according to loss, forest cover (2000), and fire status. Cells are categorized as loss if they experienced > 10% forest loss, and as forest if canopy cover in 2000 > 50%.we explored the relationships between tree cover loss and hotspots at the local scale. Of the 1 km^2 cells that experienced > 10% forest loss, 45% experienced at least one fire hotspot. In contrast, of the 1 km^2 cells that did not experience forest loss, only 13% experienced at least one fire hotspot. We found that 92% of fire hotspots occurred in pixels that were forest in 2001 (> 50% forest cover in 2000) and 8% occurred in non-forest pixels. In Kalimantan, most fires occur in non-forest areas (Noojipady et al., 2017), but the relationship with former land cover was not explored.

Table 3.5 Occurrence of hotspots in 1 km^2 cells according to loss, forest cover (2000), and fire status. Cells are categorized as loss if they experienced > 10% forest loss, and as forest if canopy cover in 2000 > 50%.

Loss Status (Number of Cells)	Forest Status	Fire Status	Number of Cells	% of Cells	Hotspot Sum	% of Hotspot
Loss (14,902)	Forest	Has fire	6632	45%	24,554	56%
	Forest	No fire	8022	55%	0	
	Sub-total (Loss-Forest)		: 14,654			
	Non forest	Has fire	45	18%	109	0.2%
	Non forest	No fire	203	82%	0	
	Sub-total (Loss-Non Forest)		: 248			
No Loss (77,598)	Forest	Has fire	8439	13%	15,979	36%
	Forest	No fire	56,751	87%	0	
	Sub-total (No loss – Forest)		: 65,190			
	Non forest	Has fire	1467	12%	3401	8%
	Non forest	No fire	10,941	88%	0	
	Sub-total (No loss – Non Forest)		:12,408			
92,500					44,043	

3.3.10 The time difference between the year of tree cover loss and the year with maximum number of hotspots

Figure 3.12 shows the time difference between the year of tree cover loss and the year with maximum number of hotspots. We restrict this analysis to tree cover loss occurring during 2005 to 2007, which are the central years in our datasets and allow for an equal number of years before and after any tree cover loss. Across all of Riau, the year with the maximum number of fire hotspots occurred within one year of the year tree cover loss in 70% of 1 km^2 cells. That indicates that in these regions, tree cover loss and fire are closely linked. In 17% of cells, the year with the maximum number of fire hotspots occurred 2 to 5 years before tree cover loss, whilst in 14% of cells, the maximum number of fire hotspots occurs between two and five years after the year of forest loss. Figure 3.13 shows the fraction of cells in which the year with maximum number of hotspots occurred within one year of tree cover loss. In peat lands, hotspots occurs in the same year as tree cover loss in 73% of cells, compared to 66% in non-peatlands. It was estimated that 25% of forest loss in Indonesia involved fire (co-located fire occurred in the same year or the year before forest loss) (Staal et al., 2018).

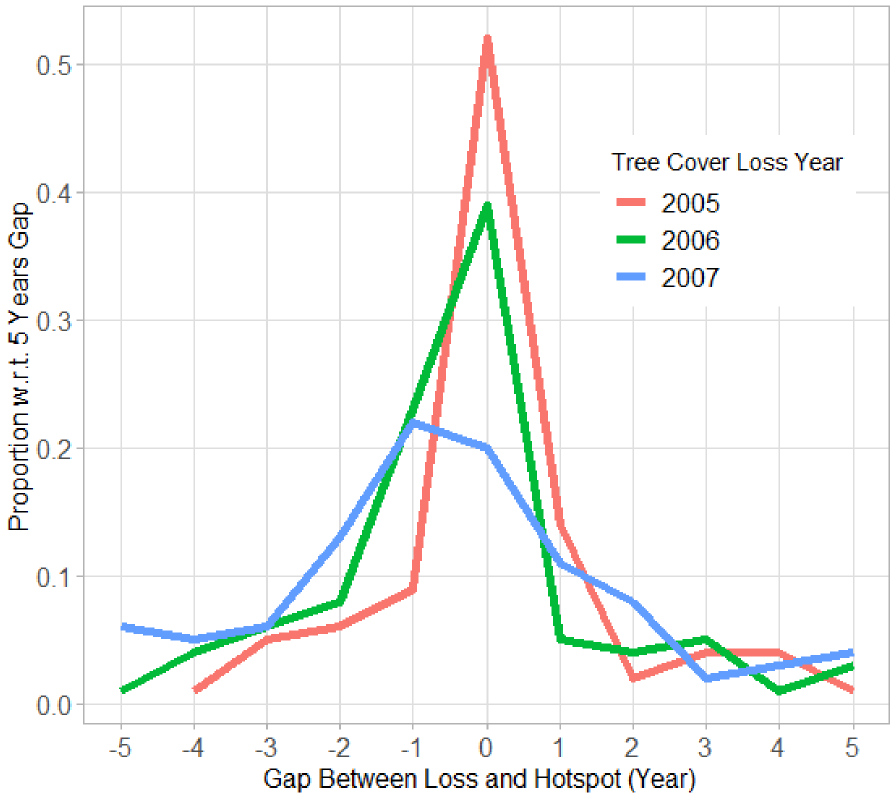

Figure 3.12. Number of years between forest loss and the year with the maximum number of fire hotspots;

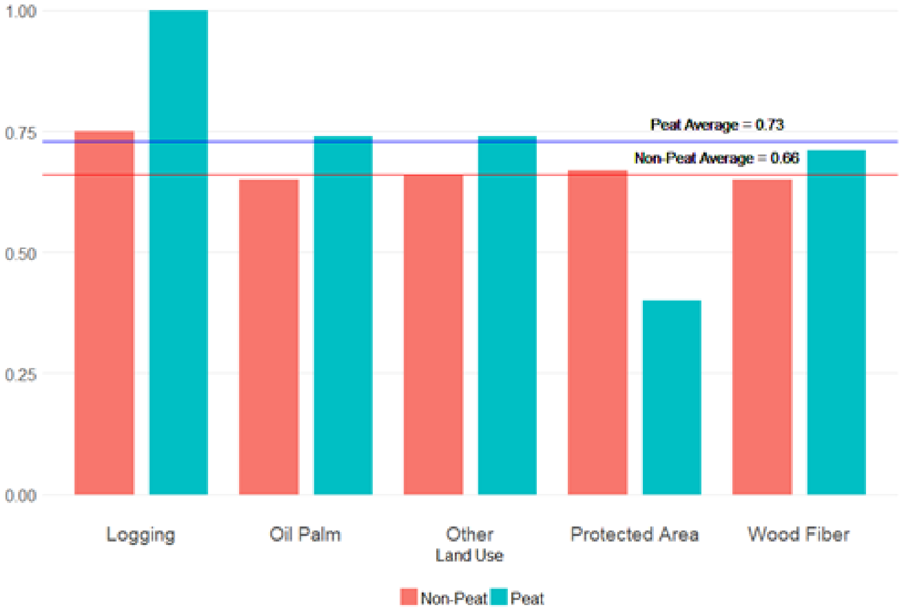

Figure 3.13 The fraction of cells where year with maximum number of hotspots occurs within +/− 1 year of forest loss

3.4 Discussion

We find that fire in Riau is closely linked to forest loss, both temporally and spatially. We show that the number of fire hotspots is a factor of 6 greater in regions of forest loss compared to regions of no loss. Fire frequency was greatest in regions that were covered in forest in 2000 and lost all their forest cover between 2001 and 2012 (Figure 3.3). We also show that forest loss and fire occur within one year of each other in 70% of 1 km^2 cells, with the frequency of hotspots substantially lower before and after forest loss (Figure 3.12).

There are two possible reasons for this observed relationship between fire and forest loss. Either the fire causes the forest loss, or forest loss makes the landscape more susceptible to fire. Since fire frequency is lower after forest loss and similar to the rate before forest loss occurred (Figure 3.12), we suggest that the loss of forest canopy is not the main cause of increased fire during the period of forest loss. Instead, it appears that the fires contribute to loss of canopy cover. In tropical regions with naturally high tree cover, fires can cause substantial tree mortality (Ferry Slik et al., 2002; Van Nieuwstadt and Sheil, 2005). A study in Kalimantan found fires cause complete mortality for small trees, but less mortality for larger trees (Sumarga, 2017). Fires are frequently ignited to clear vegetation and prepare land for agriculture and plantations (Reiche et al., 2018). Across Indonesian oil palm concessions, 25% of forest loss experienced coincident fire the same year or one year before forest loss (Staal et al., 2018). A detailed analysis of fires occurring in Riau during 1st January 2013 to 30 June 2017, found that fires in natural forests occurred on average 59±10 days before forest loss (Purnomo et al., 2017). Land in Riau that had been cleared and burnt (slashed and burnt) is worth substantially more than land that had only been cleared (Page and Hooijer, 2016), explaining a strong economic driver for the patterns we observed. The close link between forest loss and fire suggests that fire may start to decline in areas where all-natural forest has already been converted. Indeed, previous studies have shown that when oil palm extent increases to greater than 20% of a region, fire frequency declines, possibly because most areas of natural forest areas have already been lost and so forest loss rates decline (Sloan et al., 2017).

Our analysis shows that peatlands in Riau experience more frequent fire compared to non-peat regions. Forested peatlands that experienced no forest loss had the lowest frequency of fire, whilst peatland areas experiencing forest loss experienced 8 times as frequent fire. This confirms numerous studies showing the prevalence of fire on degraded peatlands (Page et al., 2011; Page et al., 2002; Tacconi, 2016). Peatlands would naturally be mostly too wet to burn. Drainage canals dug to extract timber and for establishment of oil palm plantations lower the water table and make the peat more flammable and susceptible to fire (Page et al., 2011). Reducing the frequency of fire on peatlands needs to be a priority and will require restoration, involving rewetting and re-vegetating degraded peatlands, to reduce the flammability of the landscape (Carmenta et al., 2017; Page et al., 2011). However, fire management involves a diverse range of stakeholders, meaning management interventions that aim to reduce fire are difficult to deliver (Miettinen et al., 2017).

We find that areas with high forest cover and low forest loss experience little fire. An analysis of the fires in 2015 confirms that pristine peatland forests experienced few fires even during a strong El Nino year (Staver et al., 2011). Pan-tropical studies confirm that regions with high forest cover typically have low fire frequency (Ferry Slik et al., 2002; Miettinen et al., 2012). However, in contrast to relationships seen at the pan-tropical scale, we find that areas with low tree cover and little forest loss also experience little fire. We found the greatest frequency of fire in Riau, both spatially and temporally, was connected to tree cover loss. Similarly, previous studies reported that heavily degraded forest areas in Sumatra experienced 20 times the number of fire hotspots compared to intact peatland forests (Hoscilo et al., 2011).

Regions that are classified as forest in our analysis may have been heavily degraded by logging or fire before forest loss occurs. In our analysis, areas are still defined as forest as long as they retain >50% canopy cover with vegetation > 5 m in height. Forests that have burned once are more likely to burn again (Cochrane et al., 1999). Forest degradation caused by logging or forest fragmentation can increase the flammability of the forest and the likelihood of fire (Gaveau et al., 2009; Siegert et al., 2001). In support of this, we found natural forest logging concessions on non-peat soils had a high frequency of fire. In contrast, we found natural forest logging concessions on peat soils had a very low frequency of fire, suggesting these forests were not heavily degraded. Another study on Borneo did not find any association between logging and fire (Sloan et al., 2017). Further understanding of potential feedbacks between forest degradation and fire are important, but are not well captured in our analysis, since we do not have information of the extent of forest degradation.

On peatland areas, we find that rates of forest loss and frequency of fire are typically lower in natural forest logging concessions and protected areas than other land-use types. Previous work has also found protected areas reduce deforestation in Sumatra (Spracklen et al., 2015), although lower rates of deforestation inside protected areas may partly be due to topography rather than a result of legal protection (Wijedasa et al., 2018). Policies that help support effective protected area management and efforts to grant protected area status to remaining peatland forests, 45% of which are currently unprotected (Santika et al., 2017), may reduce future forest loss and fire. Other forest management strategies may be able to play an important role. For example, community forest management in Sumatra and Kalimantan (*Hutan Desa*) reduces deforestation rates (Cattau et al., 2016b), though there are currently only very limited regions under this management scheme in Riau, so it is not possible to determine whether this could help reduce forest loss or fire in this province.

High rates of forest loss and frequent fire occur in peatland regions covered by oil palm and wood fiber concession, as well as areas outside industrial concessions, where smallholder agriculture is important (“Other”). The importance of areas outside of industrial concessions has been found by previous studies (Santika et al., 2017; Sloan et al., 2017). Wood fiber concessions and these areas outside of industrial concessions account for 80% of the increased rate of forest loss observed in Riau between 2001 and 2012. Most existing efforts to improve management of concessions focus on oil palm. Our work demonstrates a need for fire management to focus on wood fiber concessions, smallholders, and local communities. Previous studies have found a varying impact of Roundtable on Sustainable Palm Oil (RSPO) certification on forest loss and fire in oil palm concessions (Carlson et al., 2017; Gaveau et al., 2017; Staal et al., 2018). Our analysis shows that oil palm and wood fiber concessions exhibit increasing rates of forest loss but little increase in fire over the period 2001 to 2012, suggesting that conversion practices may slowly be shifting from using fire to mechanical methods for removal of forest vegetation. Some plantation companies have committed to preserve remaining natural forest in their concessions, however, we do not see any reduction in forest loss rates over the period we analyze, though we acknowledge that our analysis finishes in 2012. Ecosystem restoration licences have been obtained for two large wood fiber concession areas in Riau, allowing restoration of logged forests and degraded peatlands (Santika et al., 2017). Future work is required to demonstrate that restoration efforts can reduce fire.

Our analysis is limited by available data on concession types; overlapping concessions cause issues for relating fire and forest loss to specific concession types (Hansson and Dargusch, 2017). The satellite data we use on forest loss cannot distinguish between loss of natural forest and clearance of oil palm and wood plantations. Future work needs to explore specific land-use transitions and relate these to occurrence of fire.

3.5 Conclusions

We have explored the relationship among fire, land-use, and land-cover change in Riau Province, Indonesia, over the period 2001 to 2012. We found that at the local (1 km) scale, fire and forest loss were closely related both spatially and temporally. The majority of fire in Riau occurs in regions that are also experiencing forest loss. This finding has important implications for forest management and fire suppression efforts in Riau.

On the local scale, we found strong spatial and temporal associations between forest loss and fire. The frequency of fire was a factor of 6 greater in regions that had experienced forest loss compared to regions that had not experienced forest loss. For 70% of the 1 km2 cells experiencing forest loss, the year with the maximum number of hotspots coincided within one year of forest loss. The frequency of fire declined in the years after forest loss, confirming that fire and forest loss are closely linked.

Peatland areas experienced greater fire frequency and faster rates of forest loss compared to non-peatland areas. Hotspot density was a factor of 3 greater on peatlands compared to non-peatlands, and rates of forest loss were 30% faster on peatlands compared to those on mineral soils. There was also a close association between forest loss and fire - the frequency of fire was a factor of 8 greater in peatland areas that experienced forest loss compared to peatland regions that did not experience forest loss. Drainage of peatlands and loss of tree cover increases the flammability of peat and the likelihood of fire.

We found that different land-use types experienced widely varying rates of fire and forest loss. Of all the different land-use types, wood fiber concessions had the highest proportional rate of forest loss (5.8% yr^{-1}) and the highest hotspot density (0.06 km^{-2} yr^{-1}), whereas protected areas experienced the lowest proportional forest loss (1% yr^{-1}) and hotspot density (0.018 km^{-2} yr^{-1}). On peatlands, hotspot frequency in protected areas and logging concessions was a factor 10 to 100 lower than the hotspot frequency in oil palm and wood fiber concessions. Protected areas exhibited the lowest rates of forest loss and hotspot density on both peat and non-peat soils. Lower fire rates in protected areas and logging concessions on peatlands may be due to limited drainage and high canopy cover increasing soil moisture and reducing the potential for fire as well as a reduction in the potential for anthropogenic ignitions.

Efforts to reduce fire need to address this underlying role of land-use and land-cover change in the occurrence of fire. Supporting effective management of existing protected areas and logging concessions and expanding the protected area network to include unprotected forested peatlands may be an effective way to reduce future fire risk and forest loss. Reducing the risk of future fire will also require extensive peatland restoration, involving rewetting and revegetation of degraded peatlands (Page et al., 2011). The Indonesian Peatland Restoration Agency has a mandate to restore 2 million hectares of fire-damaged peatlands by 2020, and needs to be adequately resourced (Hansson and Dargusch, 2017). Targeting fire suppression activities to areas of natural forest adjacent to areas with recent forest loss maybe be an effective way to prioritize fire suppression capacity in period of high fire risk.

Bibliography

Albar, I. 2015. Typology Analysis of Land and Forest Fire in Riau Province, Indonesia. In: *International Workshop on Land Use/Cover Change and Air Pollution, 4-7 August 2015, Bogor*.

Austin, K.G., Schwantes, A., Gu, Y. and Kasibhatla, P.S. 2019. What Causes Deforestation in Indonesia? *Environmental Research Letters.* **14**(2), p024007.10.1088/1748-9326/aaf6db

Bappenas. 2015. *Analisis Provinsi Riau.*

Carlson, K.M., Heilmayr, R., Gibbs, H.K., Noojipady, P., Burns, D.N., Morton, D.C., Walker, N.F., Paoli, G.D. and Kremen, C. 2017. Effect of Oil Palm Sustainability Certification on Deforestation and Fire in Indonesia. *Proceedings of the National Academy of Sciences.* **115**(1), p121.10.1073/pnas.1704728114

Carmenta, R., Zabala, A., Daeli, W. and Phelps, J. 2017. Perceptions across Scales of Governance and the Indonesian Peatland Fires. *Global Environmental Change.* **46**, pp.50-59.https://doi.org/10.1016/j.gloenvcha.2017.08.001

Cattau, M.E., Harrison, M.E., Shinyo, I., Tungau, S., Uriarte, M. and DeFries, R. 2016a. Sources of Anthropogenic Fire Ignitions on the Peat-Swamp Landscape in Kalimantan, Indonesia. *Global Environmental Change.* **39**, pp.205-219.10.1016/j.gloenvcha.2016.05.005

Cattau, M.E., Marlier, M.E. and DeFries, R. 2016b. Effectiveness of Roundtable on Sustainable Palm Oil (Rspo) for Reducing Fires on Oil Palm Concessions in Indonesia from 2012 to 2015. *Environmental Research Letters.* **11**(10), p105007.10.1088/1748-9326/11/10/105007

Chisholm, R.A., Wijedasa, L.S. and Swinfield, T. 2015. The Need for Long-Term Remedies for Indonesia's Forest Fires. *Conserv Biol.* **30**(1), pp.5-6.10.1111/cobi.12662

Cochrane, M.A. 2003. Fire Science for Rainforests. *Nature.* **421**(6926), pp.913-919.10.1038/nature01437

Cochrane, M.A., Alencar, A., Schulze, M.D., Souza, C.M., Nepstad, D.C., Lefebvre, P. and Davidson, E.A. 1999. Positive Feedbacks in the Fire Dynamic of Closed Canopy Tropical Forests. *Science.* **284**(5421), p1832.10.1126/science.284.5421.1832

Cochrane, M.A. and Schulze, M.D. 1999. Fire as a Recurrent Event in Tropical Forests of the Eastern Amazon: Effects on Forest Structure, Biomass, and Species Composition. *Biotropica.* **31**(1), pp.2-16.10.2307/2663955

Crippa, P., Castruccio, S., Archer-Nicholls, S., Lebron, G.B., Kuwata, M., Thota, A., Sumin, S., Butt, E., Wiedinmyer, C. and Spracklen, D.V. 2016. Population Exposure to Hazardous Air Quality Due to the 2015 Fires in Equatorial Asia. *Sci Rep.* **6**, p37074.10.1038/srep37074

Dennis, R.A., Mayer, J., Applegate, G., Chokkalingam, U., Colfer, C., Kurniawan, I., Lachowski, H., Maus, P., Permana, R.P., Ruchiat, Y., Stolle, F., Suyanto and Tomich, T.P. 2005. Fire, People and Pixels: Linking Social Science and Remote Sensing to Understand Underlying Causes and Impacts of Fires in Indonesia. *Human Ecology.* **33**(4), pp.465-504.10.1007/s10745-005-5156-z

Dohong, A., Aziz, A.A. and Dargusch, P. 2017. A Review of the Drivers of Tropical Peatland Degradation in South-East Asia. *Land Use Policy.* **69**(Supplement C), pp.349-360.10.1016/j.landusepol.2017.09.035

Edwards, R.B. 2019. *Export Agriculture and Rural Poverty : Evidence from Indonesian Palm Oil.* [Manuscript]. At*:* Brisbane.

Ekadinata, A.E. and Dewi, S. 2011. *Estimating Losses in Aboveground Carbon Stock from Land-Use and Land-Cover Changes in Indonesia (1990, 2000, 2005).* Bogor: World Agroforestry Centre (ICRAF) Southeast Asia Program.

Eva, H. and Lambin, E.F. 1998. Remote Sensing of Biomass Burning in Tropical Regions. *Remote Sensing of Environment.* **64**(3), pp.292-315.10.1016/s0034-4257(98)00006-6

Fanin, T. and van der Werf, G.R. 2017. Precipitation–Fire Linkages in Indonesia (1997–2015). *Biogeosciences.* **14**(18), pp.3995-4008.10.5194/bg-14-3995-2017

Ferry Slik, J.W., Verburg, R.W. and Keßler, P.J.A. 2002. Effects of Fire and Selective Logging on the Tree Species Composition of Lowland Dipterocarp Forest in East Kalimantan, Indonesia. *Biodiversity and Conservation.* **11**(1), pp.85-98.10.1023/a:1014036129075

Field, R.D., van der Werf, G.R., Fanin, T., Fetzer, E.J., Fuller, R., Jethva, H., Levy, R., Livesey, N.J., Luo, M., Torres, O. and Worden, H.M. 2016. Indonesian Fire Activity and Smoke Pollution in 2015 Show Persistent Nonlinear Sensitivity to El Nino-Induced Drought. *Proc Natl Acad Sci U S A.* **113**(33), pp.9204-9209.10.1073/pnas.1524888113

Field, R.D., van der Werf, G.R. and Shen, S.S.P. 2009. Human Amplification of Drought-Induced Biomass Burning in Indonesia since 1960. *Nature Geosci.* **2**(3), pp.185-188.http://www.nature.com/ngeo/journal/v2/n3/suppinfo/ngeo443_S1.html

Gaveau, D.L.A., Epting, J., Lyne, O., Linkie, M., Kumara, I., Kanninen, M. and Leader-Williams, N. 2009. Evaluating Whether Protected Areas Reduce Tropical Deforestation in Sumatra. *Journal of Biogeography.* **36**(11), pp.2165-2175.10.1111/j.1365-2699.2009.02147.x

Gaveau, D.L.A., Pirard, R., Salim, M.A., Tonoto, P., Yaen, H., Parks, S.A. and Carmenta, R. 2017. Overlapping Land Claims Limit the Use of Satellites to Monitor No-Deforestation Commitments and No-Burning Compliance. *Conservation Letters.* **10**(2), pp.257-264.10.1111/conl.12256

Gaveau, D.L.A., Salim, M.A., Hergoualc'h, K., Locatelli, B., Sloan, S., Wooster, M., Marlier, M.E., Molidena, E., Yaen, H., DeFries, R., Verchot, L., Murdiyarso, D., Nasi, R., Holmgren, P. and Sheil, D. 2014. Major Atmospheric Emissions from Peat Fires in Southeast Asia During Non-Drought Years: Evidence from the 2013 Sumatran Fires. *Sci Rep.* **4**, p6112.10.1038/srep06112

Gaveau, D.L.A., Sheil, D., Husnayaen, Salim, M.A., Arjasakusuma, S., Ancrenaz, M., Pacheco, P. and Meijaard, E. 2016. Rapid Conversions and Avoided Deforestation: Examining Four Decades of Industrial Plantation Expansion in Borneo. *Scientific Reports.* **6**, p32017.10.1038/srep32017

https://www.nature.com/articles/srep32017#supplementary-information

Giglio, L. 2010. *Modis Collection 5 Active Fire Product User’s Guide Version 2.4.* [Manuscript]. At.

Giglio, L., Boschetti, L., Roy, D.P., Humber, M.L. and Justice, C.O. 2018. The Collection 6 Modis Burned Area Mapping Algorithm and Product. *Remote Sensing of Environment.* **217**, pp.72-85.https://doi.org/10.1016/j.rse.2018.08.005

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O. and Townshend, J.R. 2013. High-Resolution Global Maps of 21st-Century Forest Cover Change. *Science.* **342**(6160), pp.850-853.10.1126/science.1244693

Hansen, M.C., Stehman, S.V., Potapov, P.V., Margono, B.A., Stolle, F. and Pittman, K. 2009. Quantifying Changes in the Rates of Forest Clearing in Indonesia from 1990 to 2005 Using Remotely Sensed Data Sets. *Environmental Research Letters.* **4**(3), p034001.10.1088/1748-9326/4/3/034001

Hansson, A. and Dargusch, P. 2017. An Estimate of the Financial Cost of Peatland Restoration in Indonesia. *Case Studies in the Environment.*10.1525/cse.2017.000695

Hantson, S., Padilla, M., Corti, D. and Chuvieco, E. 2013. *Strengths and Weaknesses of Modis Hotspots to Characterize Global Fire Occurrence.*

Harja, D., Dewi, S., Heryawan, F. and van Noordwijk, M. 2011. *Forest Carbon-Stock Estimates Based on National Forest Inventory Data.*

Harris, N.L., Goldman, E., Gabris, C., Nordling, J., Minnemeyer, S., Ansari, S., Lippmann, M., Bennett, L., Raad, M., Hansen, M.C. and Potapov, P.V. 2017. Using Spatial Statistics to Identify Emerging Hot Spots of Forest Loss. *Environmental Research Letters.* **12**(2), p024012.10.1088/1748-9326/aa5a2f

Hoscilo, A., Page, S.E., Tansey, K.J. and Rieley, J.O. 2011. Effect of Repeated Fires on Land-Cover Change on Peatland in Southern Central Kalimantan, Indonesia, from 1973 to 2005. *International Journal of Wildland Fire.* **20**(4), p578.10.1071/wf10029

Huijnen, V., Wooster, M.J., Kaiser, J.W., Gaveau, D.L.A., Flemming, J., Parrington, M., Inness, A., Murdiyarso, D., Main, B. and van Weele, M. 2016. Fire Carbon Emissions over Maritime Southeast Asia in 2015 Largest since 1997. *Scientific Reports.* **6**, p26886.10.1038/srep26886

https://www.nature.com/articles/srep26886#supplementary-information

Juárez-Orozco, S.M., Siebe, C. and Fernández y Fernández, D. 2017. Causes and Effects of Forest Fires in Tropical Rainforests: A Bibliometric Approach. *Tropical Conservation Science.* **10**, p1940082917737207.10.1177/1940082917737207

Kiely, L., Spracklen, D.V., Wiedinmyer, C., Conibear, L., Reddington, C.L., Archer-Nicholls, S., Lowe, D., Arnold, S.R., Knote, C., Khan, M.F., Latif, M.T., Kuwata, M., Budisulistiorini, S.H. and Syaufina, L. 2019. New Estimate of Particulate Emissions from Indonesian Peat Fires in 2015. *Atmos. Chem. Phys.* **19**(17), pp.11105-11121.10.5194/acp-19-11105-2019

Koplitz, S.N., Mickley, L.J., Marlier, M.E., Buonocore, J.J., Kim, P.S., Liu, T., Sulprizio, M.P., DeFries, R.S., Jacob, D.J., Schwartz, J., Pongsiri, M. and Myers, S.S. 2016. Public Health Impacts of the Severe Haze in Equatorial Asia in September–October 2015: Demonstration of a New Framework for Informing Fire Management Strategies to Reduce Downwind Smoke Exposure. *Environmental Research Letters.* **11**(9), p094023.10.1088/1748-9326/11/9/094023

Lambin, E.F. and Ehrlich, D. 1997. The Identification of Tropical Deforestation Fronts at Broad Spatial Scales. *International Journal of Remote Sensing.* **18**(17), pp.3551-3568.10.1080/014311697216793

Langner, A., Miettinen, J. and Siegert, F. 2007. Land Cover Change 2002–2005 in Borneo and the Role of Fire Derived from Modis Imagery. *Global Change Biology.* **13**(11), pp.2329-2340.10.1111/j.1365-2486.2007.01442.x

Langner, A. and Siegert, F. 2009. Spatiotemporal Fire Occurrence in Borneo over a Period of 10 Years. *Global Change Biology.* **15**(1), pp.48-62.10.1111/j.1365-2486.2008.01828.x

Lavorel, S., Flannigan, M.D., Lambin, E.F. and Scholes, M.C. 2006. Vulnerability of Land Systems to Fire: Interactions among Humans, Climate, the Atmosphere, and Ecosystems. *Mitigation and Adaptation Strategies for Global Change.* **12**(1), pp.33-53.10.1007/s11027-006-9046-5

Margono, B.A., Potapov, P.V., Turubanova, S., Stolle, F. and Hansen, M.C. 2014. Primary Forest Cover Loss in Indonesia over 2000–2012. *Nature Climate Change.* **4**(8), pp.730-735.10.1038/nclimate2277

Marlier, M.E., DeFries, R.S., Kim, P.S., Gaveau, D.L.A., Koplitz, S.N., Jacob, D.J., Mickley, L.J., Margono, B.A. and Myers, S.S. 2015a. Regional Air Quality Impacts of Future Fire Emissions in Sumatra and Kalimantan. *Environmental Research Letters.* **10**(5), p054010.10.1088/1748-9326/10/5/054010

Marlier, M.E., DeFries, R.S., Kim, P.S., Koplitz, S.N., Jacob, D.J., Mickley, L.J. and Myers, S.S. 2015b. Fire Emissions and Regional Air Quality Impacts from Fires in Oil Palm, Timber, and Logging Concessions in Indonesia. *Environmental Research Letters.* **10**(8), p085005.10.1088/1748-9326/10/8/085005

Marlier, M.E., DeFries, R.S., Voulgarakis, A., Kinney, P.L., Randerson, J.T., Shindell, D.T., Chen, Y. and Faluvegi, G. 2013. El Niño and Health Risks from Landscape Fire Emissions in Southeast Asia. *Nature climate change.* **3**, pp.131-136.10.1038/nclimate1658

Meijaard, E. and Sheil, D. 2019. The Moral Minefield of Ethical Oil Palm and Sustainable Development. *Frontiers in Forests and Global Change.* **2**, p22

Miettinen, J., Hooijer, A., Wang, J., Shi, C. and Liew, S.C. 2012. Peatland Degradation and Conversion Sequences and Interrelations in Sumatra. *Regional Environmental Change.* **12**(4), pp.729-737.10.1007/s10113-012-0290-9

Miettinen, J. and Liew, S.C. 2005. Connection between Fire and Land Cover Change in Southeast Asia: A Remote Sensing Case Study in Riau, Sumatra. *International Journal of Remote Sensing.* **26**(6), pp.1109-1126.10.1080/01431160512331326756

Miettinen, J., Shi, C. and Liew, S.C. 2017. Fire Distribution in Peninsular Malaysia, Sumatra and Borneo in 2015 with Special Emphasis on Peatland Fires. *Environ Manage.* **60**(4), pp.747-757.10.1007/s00267-017-0911-7

Noojipady, P., Morton, D.C., Schroeder, W., Carlson, K.M., Huang, C., Gibbs, H.K., Burns, D., Walker, N.F. and Prince, S.D. 2017. Managing Fire Risk During Drought: The Influence of Certification and El Niño on Fire-Driven Forest Conversion for Oil Palm in Southeast Asia. *Earth System Dynamics.* **8**(3), pp.749-771.10.5194/esd-8-749-2017

Page, S.E. and Hooijer, A. 2016. In the Line of Fire: The Peatlands of Southeast Asia. *Philos Trans R Soc Lond B Biol Sci.* **371**(1696), p20150176.http://dx.doi.org/10.1098/rstb.2015.0176

Page, S.E., Rieley, J.O. and Banks, C.J. 2011. Global and Regional Importance of the Tropical Peatland Carbon Pool. *Global Change Biology.* **17**(2), pp.798-818.https://doi.org/10.1111/j.1365-2486.2010.02279.x

Page, S.E., Siegert, F., Rieley, J.O., Boehm, H.D., Jaya, A. and Limin, S. 2002. The Amount of Carbon Released from Peat and Forest Fires in Indonesia During 1997. *Nature.* **420**(6911), pp.61-65.10.1038/nature01131

Pramudya, E.P., Hospes, O. and Termeer, C.J.A.M. 2018. The Disciplining of Illegal Palm Oil Plantations in Sumatra. *Third World Quarterly.* **39**(5), pp.920-940.10.1080/01436597.2017.1401462

Prasetyo, L.B., Dharmawan, A.H., Nasdian, F.T. and Ramdhoni, S. 2016. Historical Forest Fire Occurrence Analysis in Jambi Province During the Period of 2000 – 2015: Its Distribution & Land Cover Trajectories. *Procedia Environmental Sciences.* **33**, pp.450-459.10.1016/j.proenv.2016.03.096

Purnomo, H., Shantiko, B., Sitorus, S., Gunawan, H., Achdiawan, R., Kartodihardjo, H. and Dewayani, A.A. 2017. Fire Economy and Actor Network of Forest and Land Fires in Indonesia. *Forest Policy and Economics.* **78**, pp.21-31.10.1016/j.forpol.2017.01.001

Reddington, C.L., Yoshioka, M., Balasubramanian, R., Ridley, D., Toh, Y.Y., Arnold, S.R. and Spracklen, D.V. 2014. Contribution of Vegetation and Peat Fires to Particulate Air Pollution in Southeast Asia. *Environmental Research Letters.* **9**(9), p094006

Reiche, J., Verhoeven, R., Verbesselt, J., Hamunyela, E., Wielaard, N. and Herold, M. 2018. Characterizing Tropical Forest Cover Loss Using Dense Sentinel-1 Data and Active Fire Alerts. *Remote Sensing.* **10**(5).10.3390/rs10050777

Santika, T., Meijaard, E., Budiharta, S., Law, E.A., Kusworo, A., Hutabarat, J.A., Indrawan, T.P., Struebig, M., Raharjo, S., Huda, I., Sulhani, Ekaputri, A.D., Trison, S., Stigner, M. and Wilson, K.A. 2017. Community Forest Management in Indonesia: Avoided Deforestation in the Context of Anthropogenic and Climate Complexities. *Global Environmental Change.* **46**, pp.60-71.https://doi.org/10.1016/j.gloenvcha.2017.08.002

Siegert, F., Ruecker, G., Hinrichs, A. and Hoffmann, A.A. 2001. Increased Damage from Fires in Logged Forests During Droughts Caused by El Nino. *Nature.* **414**(6862), pp.437-440.10.1038/35106547

Sloan, S., Locatelli, B., Wooster, M.J. and Gaveau, D.L.A. 2017. Fire Activity in Borneo Driven by Industrial Land Conversion and Drought During El Niño Periods, 1982–2010. *Global Environmental Change.* **47**, pp.95-109.https://doi.org/10.1016/j.gloenvcha.2017.10.001

Spracklen, B.D., Kalamandeen, M., Galbraith, D., Gloor, E. and Spracklen, D.V. 2015. A Global Analysis of Deforestation in Moist Tropical Forest Protected Areas. *PLoS One.* **10**(12), pe0143886.10.1371/journal.pone.0143886

Staal, A., van Nes, E.H., Hantson, S., Holmgren, M., Dekker, S.C., Pueyo, S., Xu, C. and Scheffer, M. 2018. Resilience of Tropical Tree Cover: The Roles of Climate, Fire, and Herbivory. *Global Change Biology.* **24**(11), pp.5096-5109.10.1111/gcb.14408

Staver, A.C., Archibald, S. and Levin, S.A. 2011. The Global Extent and Determinants of Savanna and Forest as Alternative Biome States. *Science.* **334**(6053), p230.10.1126/science.1210465

Sumarga, E. 2017. Spatial Indicators for Human Activities May Explain the 2015 Fire Hotspot Distribution in Central Kalimantan Indonesia. *Tropical Conservation Science.* **10**, p1940082917706168.10.1177/1940082917706168

Suyanto, Applegate, G., Permana, R.P., Khususiyah, N. and Kurniawan, I. 2004. The Role of Fire in Changing Land Use and Livelihoods in Riau - Sumatera.Pdf. *Ecology and Society.* **9**(1), p15

Tacconi, L. 2016. Preventing Fires and Haze in Southeast Asia. *Nature Climate Change.* **6**, p640.10.1038/nclimate3008

Taufik, M., Torfs, P.J.J.F., Uijlenhoet, R., Jones, P.D., Murdiyarso, D. and Van Lanen, H.A.J. 2017. Amplification of Wildfire Area Burnt by Hydrological Drought in the Humid Tropics. *Nature Climate Change.* **7**, p428.10.1038/nclimate3280

https://www.nature.com/articles/nclimate3280#supplementary-information

van der Werf, G.R., Dempewolf, J., Trigg, S.N., Randerson, J.T., Kasibhatla, P.S., Giglio, L., Murdiyarso, D., Peters, W., Morton, D.C., Collatz, G.J., Dolman, A.J. and DeFries, R.S. 2008. Climate Regulation of Fire Emissions and Deforestation in Equatorial Asia. *Proc Natl Acad Sci U S A.* **105**(51), pp.20350-20355.10.1073/pnas.0803375105

Van Nieuwstadt, M.G.L. and Sheil, D. 2005. Drought, Fire and Tree Survival in a Borneo Rain Forest, East Kalimantan, Indonesia. *Journal of Ecology.* **93**(1), pp.191-201.10.1111/j.1365-2745.2004.00954.x

Wijedasa, L.S., Jauhiainen, J., Könönen, M., Lampela, M., Vasander, H., Leblanc, M.-C., Evers, S., Smith, T.E.L., Yule, C.M., Varkkey, H., Lupascu, M., Parish, F., Singleton, I., Clements, G.R., Aziz, S.A., Harrison, M.E., Cheyne, S., Anshari, G.Z., Meijaard, E., Goldstein, J.E., Waldron, S., Hergoualc'h, K., Dommain, R., Frolking, S., Evans, C.D., Posa, M.R.C., Glaser, P.H., Suryadiputra, N., Lubis, R., Santika, T., Padfield, R., Kurnianto, S., Hadisiswoyo, P., Lim, T.W., Page, S.E., Gauci, V., Van Der Meer, P.J., Buckland, H., Garnier, F., Samuel, M.K., Choo, L.N.L.K., O'Reilly, P., Warren, M., Suksuwan, S., Sumarga, E., Jain, A., Laurance, W.F., Couwenberg, J., Joosten, H., Vernimmen, R., Hooijer, A., Malins, C., Cochrane, M.A., Perumal, B., Siegert, F., Peh, K.S.H., Comeau, L.-P., Verchot, L., Harvey, C.F., Cobb, A., Jaafar, Z., Wösten, H., Manuri, S., Müller, M., Giesen, W., Phelps, J., Yong, D.L., Silvius, M., Wedeux, B.M.M., Hoyt, A., Osaki, M., Hirano, T., Takahashi, H., Kohyama, T.S., Haraguchi, A., Nugroho, N.P., Coomes, D.A., Quoi, L.P., Dohong, A., Gunawan, H., Gaveau, D.L.A., Langner, A., Lim, F.K.S., Edwards, D.P., Giam, X., Van Der Werf, G., Carmenta, R., Verwer, C.C., Gibson, L., Gandois, L., Graham, L.L.B., Regalino, J., Wich, S.A., Rieley, J., Kettridge, N., Brown, C., Pirard, R., Moore, S., Capilla, B.R., Ballhorn, U., Ho, H.C., Hoscilo, A., Lohberger, S., Evans, T.A., Yulianti, N., Blackham, G., Onrizal, Husson, S., Murdiyarso, D., Pangala, S., Cole, L.E.S., Tacconi, L., Segah, H., Tonoto, P., Lee, J.S.H., Schmilewski, G., Wulffraat, S., Putra, E.I., Cattau, M.E., Clymo, R.S., Morrison, R., Mujahid, A., Miettinen, J., Liew, S.C., Valpola, S., Wilson, D., D'Arcy, L., Gerding, M., Sundari, S., Thornton, S.A., Kalisz, B., Chapman, S.J., Su, A.S.M., Basuki, I., Itoh, M., Traeholt, C., Sloan, S., Sayok, A.K. and Andersen, R. 2017. Denial of Long-Term Issues with Agriculture on Tropical Peatlands Will Have Devastating Consequences. *Global Change Biology.* **23**(3), pp.977-982.10.1111/gcb.13516

Wijedasa, L.S., Sloan, S., Page, S.E., Clements, G.R., Lupascu, M. and Evans, T.A. 2018. Carbon Emissions from South-East Asian Peatlands Will Increase Despite Emission-Reduction Schemes. *Global Change Biology.* **24**(10), pp.4598-4613.10.1111/gcb.14340

Chapter 4
Forest and Land Fires are Mainly Associated with Deforestation in Riau Province, Indonesia

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Abstract: Indonesia has experienced extensive land-cover change and frequent vegetation and land fires in the past few decades. We combined a new land-cover dataset with satellite data on the timing and location of fires to make the first detailed assessment of the association of fire with specific land-cover transitions in Riau, Sumatra. During 1990 to 2017, secondary peat swamp forest declined in area from 40,000 to 10,000 km^2 and plantations (including oil palm) increased from around 10,000 to 40,000 km^2. The dominant land use transitions were secondary peat swamp forest converting directly to plantation, or first to shrub and then to plantation. During 2001–2017, we find that the frequency of fire is greatest in regions that change land-cover, with the greatest frequency in regions that transition from secondary peat swamp forest to shrub or plantation (0.15 km^{-2} yr^{-1}). Areas that did not change land cover exhibit lower fire frequency, with shrub (0.06 km^{-2} yr^{-1}) exhibiting a frequency of fire >60 times the frequency of fire in primary forest. Our analysis demonstrates that in Riau, fire is closely connected to land-cover change, and that the majority of fire is associated with the transition of secondary forest to shrub and plantation. Reducing the frequency of fire in Riau will require enhanced protection of secondary forests and restoration of shrub to natural forest.

Keywords: forest and land fire; land-cover transition; Riau Indonesia

4.1 Introduction

Vegetation and peat fires in Indonesia are a major environmental hazard. Fires emit substantial amounts of CO_2 and contribute to climate change. In 2015, fires were estimated to have emitted around 700–800 Tg CO_2 (Huijnen et al., 2016; Kiely et al., 2019). Trace gas and particulate emissions from fire cause regional air pollution (Marlier et al., 2013). In September and October 2015, over 60 million people in Sumatra, Borneo, Malaysia and Singapore were exposed to poor air quality from fires (Crippa et al., 2016), contributing to 10,000–100,000 premature deaths (Crippa et al., 2016; Koplitz et al., 2016). Indonesia contains large areas of peatland. When fires burn on peat, they can burn deep into organic soils resulting in substantial emissions (Page et al., 2002). During the 2015 fires in Indonesia, peat burning contributed 55% of CO_2 emissions and 70% of primary fine particulate matter emissions from fires (Kiely et al., 2019).

In the wet tropics where annual mean rainfall is >1500 mm, fire is normally a rare occurrence (Staal et al., 2018). In Indonesia, fires are more common in dry years associated with positive ENSO index (El Niño) (Field et al., 2016), but in recent years fires also occur even in non-drought years (Gaveau et al., 2014). The clearing of forests (Hansen et al., 2013; Margono et al., 2014; Vadrevu et al., 2017) and drainage of peatlands, largely to establish oil palm and acacia plantations (Gaveau et al., 2016), has made the landscape more susceptible to fire. Fire often occurs in forested regions that are experiencing land-cover change (Vadrevu et al., 2019). Fire frequency is typically higher in oil palm and wood fibre concessions compared to protected areas (Marlier et al., 2015). Fire is used as part of the land-conversion process, to clear vegetation in preparation for agriculture and plantations (Carmenta et al., 2011). In Riau, Indonesia, fires are six times more frequent in regions experiencing recent tree cover loss compared to regions with no loss (Adrianto et al., 2019).

Understanding the links between land-cover change and fire is necessary to inform land and fire management and fire suppression efforts. However, there is still poor understanding of the fraction of fire that is associated with specific land-cover changes. Satellite datasets provide some information on land-cover change (i.e., canopy cover loss), but there is rarely detailed information on the specific land-cover transitions that occur. Here we combine a new land-cover dataset with information on the location and timing of fires from satellite, to make the first assessment of the association between fire and specific land-cover transitions in Indonesia. We focus on Riau province, one of the most active areas of fire in Indonesia.

4.2 Materials and Methods

Our study area consists of the province of Riau, Sumatra, covering 89 691 km^2 and consisting of 43% peatland (Adrianto et al., 2019). We used the land-cover map provided by the Indonesian Ministry of Environment and Forestry (http://webgis.menlhk.go.id:8080/pl/pl.htm, (Margono et al., 2016)). The map includes land-cover classifications for 1990, 1996, 2000, 2003, 2006 and 2009, then annually between 2011 and 2017. Before 2000, the land-cover classification was conducted as a part of National Forest Inventory (NFI) project which predominantly relied on analysis of Landsat imagery. During 2000–2009, digital Landsat images were combined with 1000 m SPOT Vegetation and 250 m MODIS images, but the classification still depended on visual image interpretation. Finally, since 2009 only Landsat images have been used as main data source and Landsat 8 OLI have been used since 2013. The land-cover dataset includes 31,785 polygons, with land-cover divided into 23 different land-cover classifications (Table 2.6) which we use to form nine grouped land-cover classes (Table 2.7). We also used data on the location of concession areas (wood fibre, logging, and oil palm plantation) and protected area extents in 2010 provided by the World Resources Institute (http://data.globalforestwatch.org/datasets). Concessions include oil palm, wood fibre, and logging concessions.

Information on the distribution of fire is available from thermal anomaly (active fire) products and burned area observations. Small fires that are below the detection limit of burned areas products can contribute 60% of total burned area in Equatorial Asia (Randerson et al., 2012). Here we used data from active fire products which provide more accurate data on the distribution of small fires (Randerson et al., 2012). The occurrence of fires was obtained from MODIS (Moderate Resolution Imaging Spectro-radiometer) on Terra/Aqua Satellites. The instrument has a spatial resolution of 1 km^2 resolution in the nadir (Giglio et al., 2016). We used the MCD14ML Global Monthly Fire Location Product Collection 6, with a minimum detection size of ≈50 m^2 fires under pristine conditions (Giglio et al., 2018). This product has 1.2% global daytime commission error (Giglio et al., 2016) and is suitable in describing the spatial arrangement of fire over various vegetation types (Vadrevu et al., 2013). In addition, MCD14ML may act as a good predictor for small burned area (Fornacca et al., 2017). In this research, hotspots during 2001–2017 were obtained from https://firms.modaps.eosdis.nasa.gov/download/. The Indonesian Ministry of Environment and Forestry classify hotspots pixel based on their confidence level as low confidence (<30%), medium confidence (30%–79%) and high confidence (80%–100%). (Ankerst et al.). We followed this procedure and only analysed high confidence hotspots. We defined fire frequency as the number of hotspots detected per unit area per year (km^{-2} $year^{-1}$).

We used the land-cover dataset to identify regions that have experienced land-cover transitions and regions that have not changed land cover. For 2003–2017 when we had overlapping information on land-cover and active fires, we calculated the fire frequency for different land-covers and land-cover transitions.

4.3 Result

4.3.1 Land-cover change across Riau between 1990 and 2017

Between 1990 and 2017 there has been a steady decline in natural forest cover in Riau and an expansion of plantation (PLT), shrub (SRB) and agriculture (AGR) (Figure 4.1). Secondary peat swamp forest (SSF) declined from an area of around 40 000 km^2 in 1990 to around to 10,000 km^2 in 2017. The rate of loss of SSF was fairly constant between 1990 and 2012, with slower loss between 2012 and 2017. Secondary dryland forest (SDF) also decreased, from around 15,000 km^2 to less than 3000 km^2 in 2017. Primary forest was already quite diminished in 1990, with only 2133 km2 of primary swamp forest (PSF) and 1648 km^2 of primary dryland forest (PDF) remaining. Primary forest decreased further between 1990 and 2017, with the area of PSF decreasing to 562 km^2 and the area of PDF reducing to 1502 km^2. The area of plantation increased steadily, from around 10,000 km^2 in 1990 to around 40,000 km^2 in 2017. The area of shrub increased from around 10,000 km^2 in 1990 to a maximum of around 23,000 km^2 in 2012, before declining to around 15,000 km^2 in 2017. Agriculture also expanded from around 10,000 km^2 in 1990 to 15,000 km^2 in 2017.

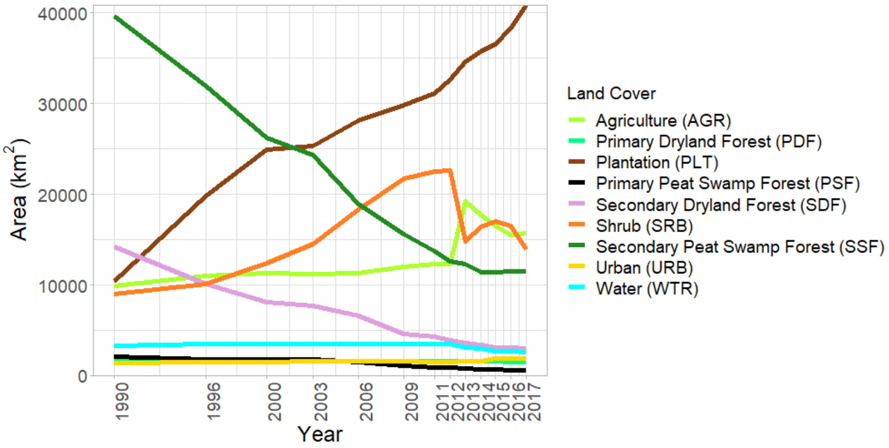


Figure 4.1 Land-cover change across Riau between 1990 and 2017

Figure 4.2 shows the major temporal (4–6 years gap) land-cover transitions that have occurred over this period. Secondary forest (dryland SDF and swamp SSF) has primarily been converted into plantation both directly (1996–2012) or via a transition to shrub then to plantation (2012–2017). Notably, there is less conversion of secondary forest since 2012.

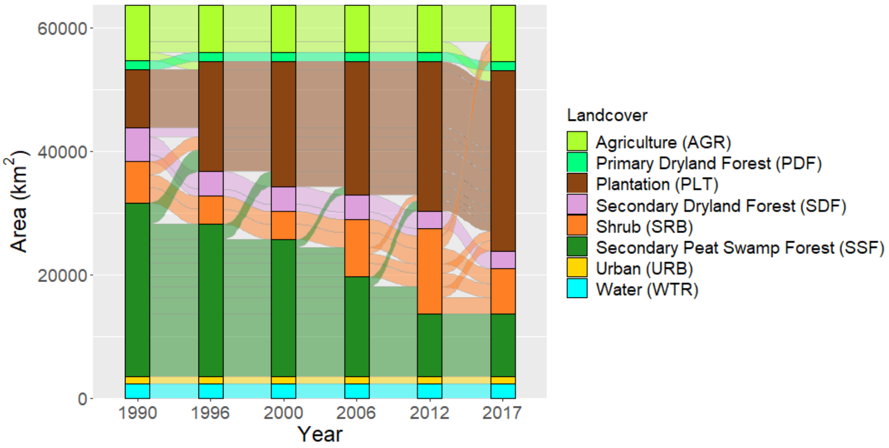
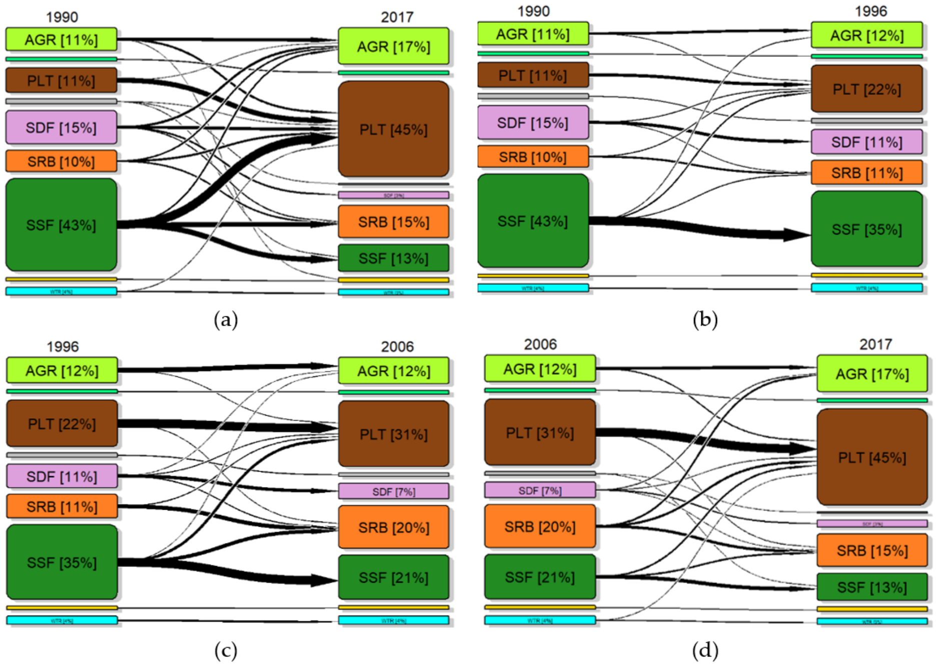


Figure 4.2 Major land-cover transitions in Riau.

Figure 4.3 shows the timings of the major land-cover transitions. The largest transitions were SSF to plantation (12,285 km^2) and shrub (14,611 km^2) and shrub to plantation (11,092 km^2) (Table 2). In 1990–1996, SSF declined from 43% to 35% (Figure 4.3b), converted to plantation (3781 km^2), shrub (2286 km^2) and agriculture (1700 km^2) (Table 2). Between 1996 and 2006, SSF declined from 35% to 21%, converted into shrub (8175 km^2) and plantation (4523 km^2) (Figure 4.3c). During 2006–2017, the largest conversions were shrub to agriculture (5000 km^2) and shrub to plantation (6000 km^2) (Figure 4.3d, Table 2).



(a) (b) (c) (d)

Figure 4.3 Land cover transitions occurring between (a) 1990 and 2017, (b) 1990 and 1996, (c) 1996 and 2006, (d) 2006 and 2017. Land cover codes are AGR: Agriculture, PDF: Primary Dryland Forest, PLT: Plantation, PSF: Primary Peat Swamp Forest, SDF: Secondary Dryland Forest, SRB: Shrub, SSF: Secondary Peat Swamp Forest.

Table 4.1Summary of the area of the main land-cover transitions (km^2) in Riau.

Initial Type	End Type	Transition	1990–1996	1996–2000	2000–2006	2006–2017	Sum
Secondary Peat Swamp Forest	Plantation	SSF→PLT	3781	2698	1825	3981	12,285
	Shrub	SSF→SRB	2286	2462	5713	4150	14,611
	Agriculture	SSF→AGR	1700	485	76	487	2748
Secondary Dryland Forest	Plantation	SDF→PLT	2012	738	235	1259	4244
	Shrub	SDF→SRB	1422	981	1182	615	4200
	Agriculture	SDF→AGR	583	347	77	1751	2758
Shrub	Plantation	SRB→PLT	2417	1016	1912	5747	11,092
	Agriculture	SRB→AGR	376	205	54	4742	5377

4.3.2 Average fire frequency for different land-covers and land-cover transitions between 2003 and 2017.

Figure 4.4 shows the average fire frequency, both for regions that have not changed land-cover type and for areas that have changed land-cover. Results were analysed for the period 2003 to 2017, when we had overlapping data on land-cover and active fires. Regions that do not change land-cover type have lower fire frequency (<0.025 km^{-2} yr^{-1} except in shrub), compared to regions that experience a land-cover transition (up to 0.15 km^{-2} yr^{-1}). The greatest fire frequency occurred in secondary peat swamp forest converted to shrub or plantation (≈0.14 km^{-2} yr^{-1}), shrub converted to plantation (0.1 km^{-2} yr^{-1}) and secondary dry forests converted to plantation (0.09 km^{-2} yr^{-1}) or agriculture (0.06 km^{-2} yr^{-1}). Of the regions that changed land-cover type, agriculture to plantation had the lowest fire frequency (0.02 km^{-2} yr^{-1}), likely because there was less need to use fire to clear vegetation from the land during this conversion.

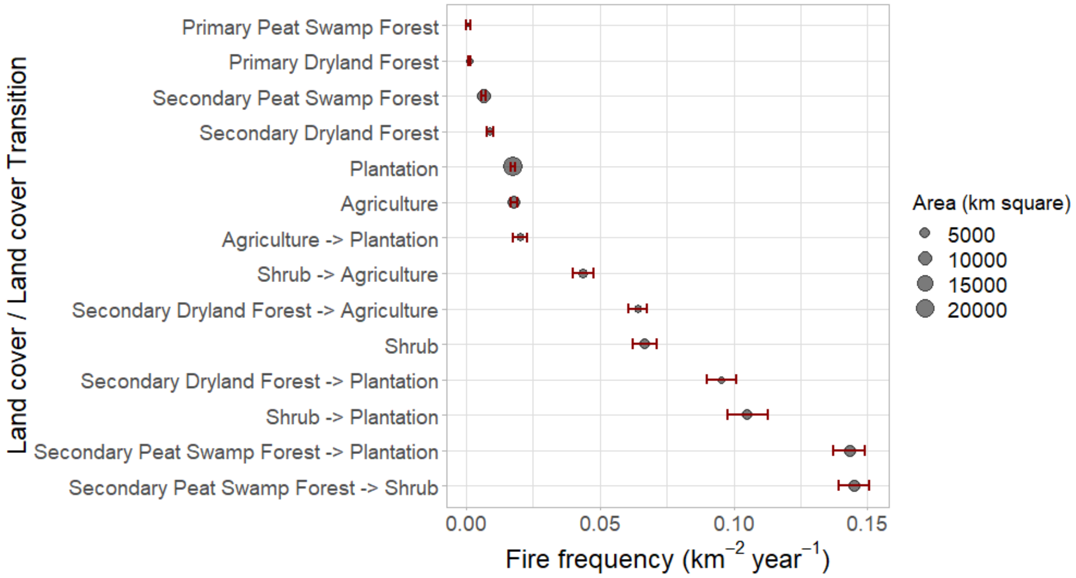


Figure 4.4 Average fire frequency for different land-covers and land-cover transitions between 2003 and 2017. Average fire frequency (point) and their 95% confidence interval (bar). Size of point shows the area of land-covers and land-cover transitions (detailed in Table 4-1).

Within regions that do not change land-cover, shrub (0.067 km^{-2} yr^{-1}) has the greatest fire frequency, several times higher than agriculture (0.018 km^{-2} yr^{-1}) or plantation (0.017 km^{-2} yr^{-1}). Primary wet and primary dry forests experience a very low fire frequency (0.001 km^{-2} yr^{-1}), a factor of 67 less than experienced in shrub regions and a factor of 17–18 less than in plantation or agriculture. Secondary dry and secondary peat swamp forest also experience low fire frequency (0.009 and 0.006 km^{-2} yr^{-1}, respectively), a factor of 7 less than shrub and half the frequency experienced in agriculture or plantation.

4.3.3 Fire frequency changes over time

Figure 4.5 shows how fire frequency has changed over time both for regions that did not experience a land-cover transition (Figure 4.5a) and regions that did (Figure 4.5b). Over 2002–2016, fire frequency has declined in agriculture and plantation land covers but has increased in secondary swamp and secondary dry forests. This may possibly indicate an increasing degradation of secondary forests over this period, increasing the potential for fire. Fire frequency in primary forests has remained very low over the whole period. Figure 4.5 emphasizes the risk of fire in shrub, since all land cover that suffers hotspot density larger than 0.1 km^{-2} yr^{-1} involved shrub. However, shrub areas which changed into plantation or agriculture had lower fire frequency after the land-cover transition. For land-cover transitions involving conversion of secondary forest to shrub, the greatest fire frequency typically coincides with the timing of the land-cover transition. After the land-cover has transitioned to shrub, fire frequency remains enhanced demonstrating a permanent transition to a more fire-prone state.

4.3.4 The frequency of fire across land-cover types and transitions

Figure 4.6 shows the frequency of fire across land-cover types and transitions, separately for different land-use concessions. In shrub areas, the greatest fire frequency occurs in oil palm and wood fibre concessions. In secondary forests the greatest fire frequency also occurs in oil palm concessions. In shrub areas that were converted to plantation, the most frequent fires occur in oil palm concessions and areas of land outside of concessions or protected areas (Other).

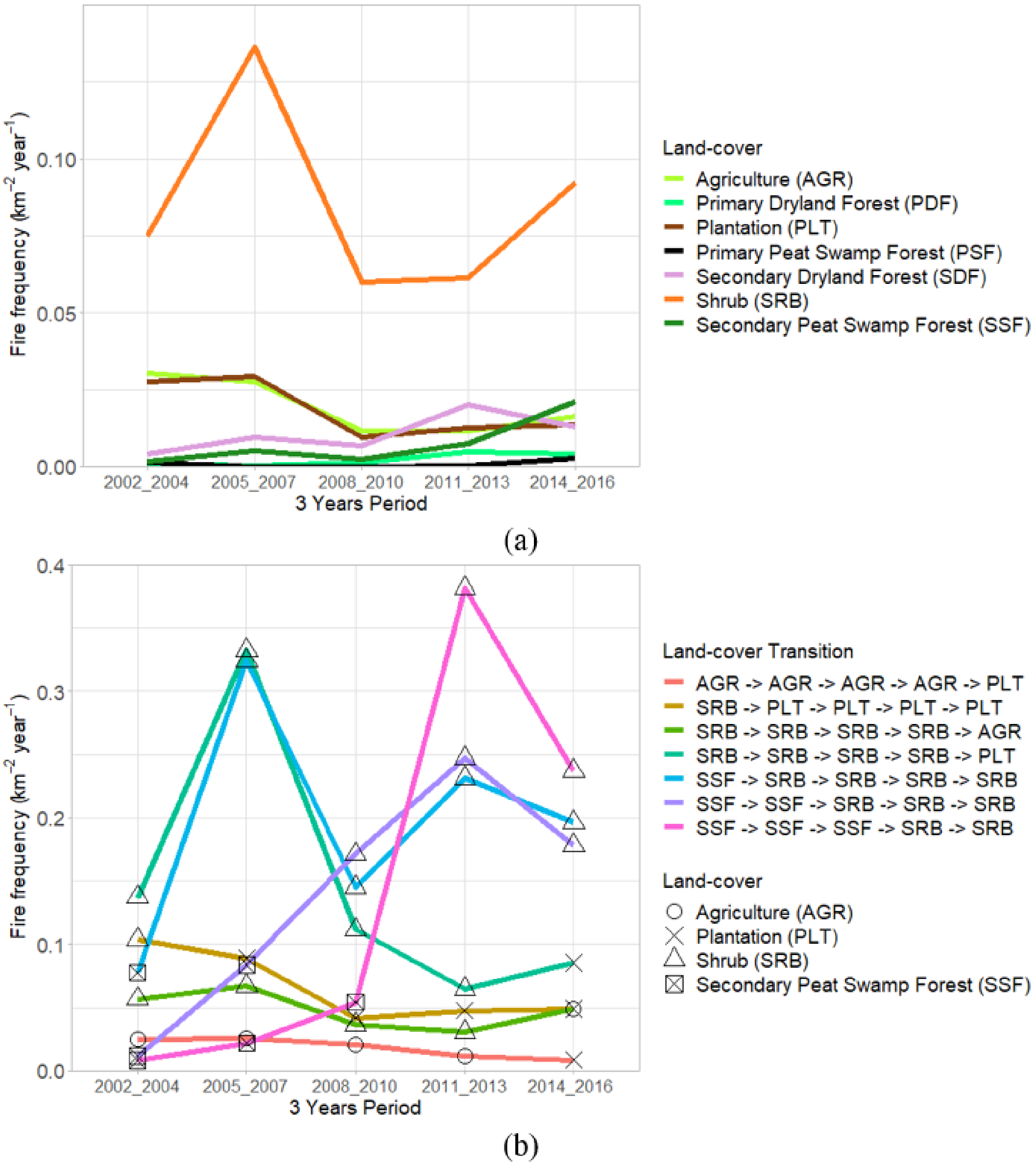
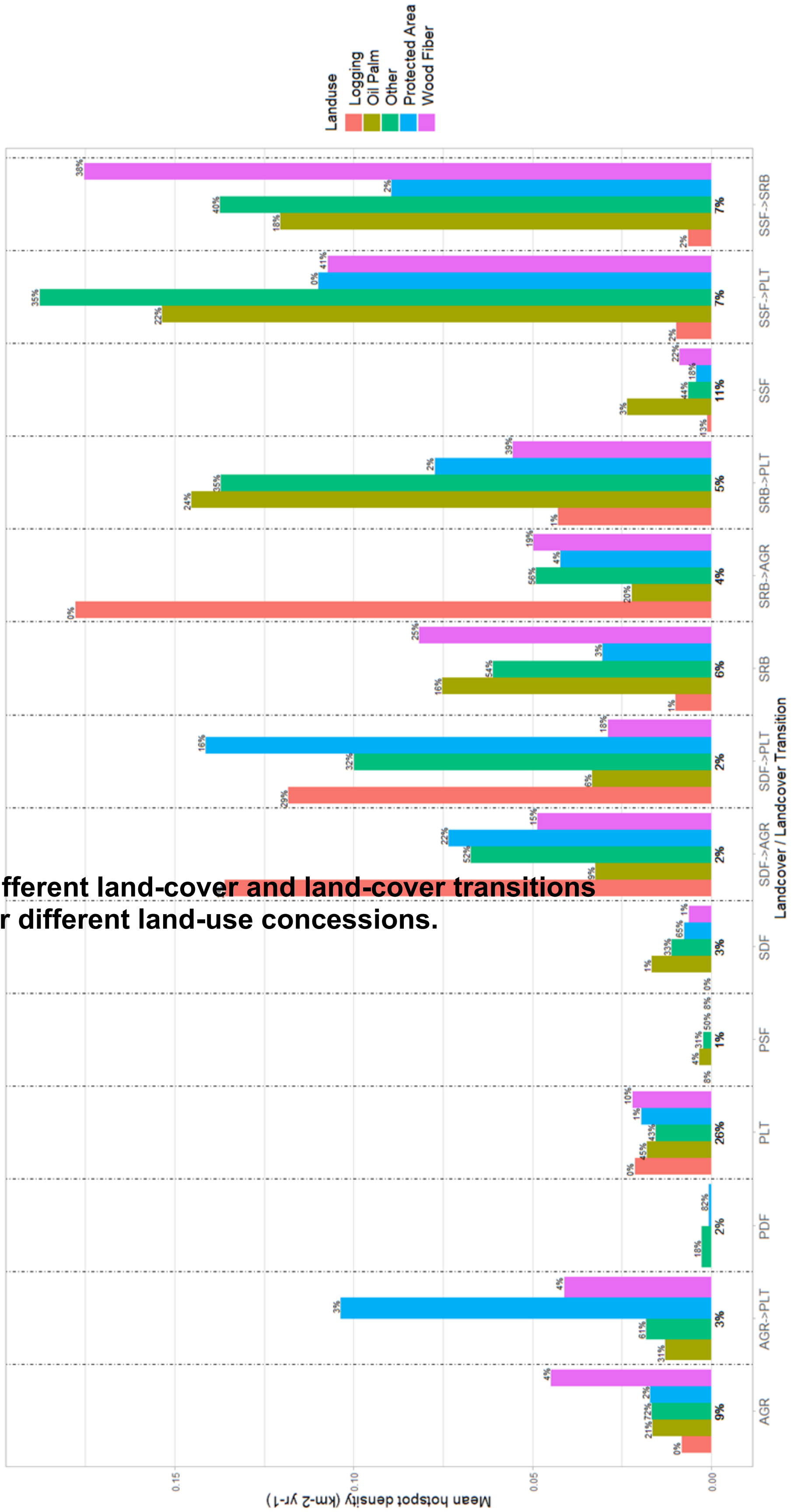


Figure 4.5 Frequency of fire according to (a) land-cover type and (b) land-cover transition, for the largest land-cover transitions (>1000 km2). Land-cover taken from year in the centre of period. Hotspot density is calculated as the average of three years surrounding the land-cover transition



ot density (km–2 yr–1) for different land-cover and land-cover transitions 2003 and 2017, separated for different land-use concessions.

4.4 Discussion

Our analysis shows that the greatest fire frequency in Riau Province, Sumatra, occurs in regions that have been converted from secondary peat swamp forest to shrub and plantation. Previous studies have shown fire in Indonesia often occurs in forested regions (Vadrevu et al., 2019). Our analysis demonstrates that this is linked to transition of forest to other land-covers. Highest fire frequency coincides with timing of the land-cover transition, confirming that fire is often used to carry out land use changes (Tacconi et al., 2007).

Shrub experienced the highest fire frequency, with lower fire frequency in plantation or agriculture areas. We find that shrub is often a transition land-cover type between secondary forest and plantation or agriculture (Figure 4.2). Shrub may be less carefully managed than other land-covers and land ownership may be less established, meaning any fire is less likely to be quickly suppressed. In 2017, shrub covered 15% of Riau.

Natural forest areas that did not experience a land-cover transition experienced the lowest fire frequency compared to other land-covers, reflecting the low susceptibility of natural forests to fire. In particular, primary forests experienced a very low fire frequency, more than a factor of 60 less than shrub. Secondary forests experienced six times more fire than primary forests, but still a factor of 6–7 less than shrub. Protecting remaining primary forests is important, but these forests now cover less than 13% of Riau's forest. Secondary forest now accounts for 87% of natural forest in Riau. The moratorium on development of plantations on primary forests (Busch et al., 2015) will therefore only prohibit plantation development from a relatively small land area within Riau. Extending this moratorium to include secondary forests would likely lead to much larger reduction in fire. Our analysis further establishes the need to protect secondary forests, which have previously been shown to be important for carbon sequestration (Chazdon, Robin L. et al., 2016) and protection of biodiversity (Chazdon, R. L. et al., 2009; Gardner et al., 2009).

A link between land-cover change and fire has been shown previously. Analysis of Sumatran fires in 2013 found that 58% of fires occurred on land that had been forest 5 years previously (Gaveau et al., 2014). Across Indonesia, 25% of forest loss in oil palm concessions experienced coincident fire the same year or one year before forest loss (Noojipady et al., 2017). In Riau, active fires were found to occur on average 58 ± 10 days before loss of natural forest (Reiche et al., 2018), further confirming the very tight association between fire and forest loss. In Chapter 3 we found that in Riau, fire frequency was a factor of 6 greater in regions that experienced forest canopy loss, compared to regions with no loss. Analysis of 2015 fires in Sumatra found that rainfall, slope and population density were the most important variables in prediction of fires at regional and 1 km^2 pixel scale (Sze et al., 2019). Fire management efforts in Indonesia need to consider the links between land-cover change and fire, the low fire frequency in undisturbed natural forest and the higher fire frequency in degraded landscapes covered by shrub. Our analysis confirms that the Indonesian Peatland Restoration Agency plans to rewet and revegetate peatlands (Harrison et al., 2019), should help to reduce the risk of fire.

Links between land-cover change and fire have also been demonstrated in the Amazon, with most fires in the 2000s linked to conversion of forest to agricultural land (Morton et al., 2008). At a regional scale, there is a positive relationship between deforestation rate and fire emissions over the period 2001 to 2012 (Reddington et al., 2015). Over the period 1990 to 2014, Amazon-wide forest loss explained 31% of the variability in Amazon fire emissions (van Marle et al., 2017). Other studies have found that in the Rondônia and Mato Grosso regions of Amazonia, 53% of fires in 2005 occurred in land that had been deforested within the prior 5 years (Lima et al., 2012). Areas of cleared Amazon broadleaf forest were very likely to burn shortly after forest cover loss, with 46% burning with 5 years (Fanin and van der Werf, 2015). An increased frequency of fire in regions with declining deforestation rate in primary forests, may be due to increased loss of secondary forest (Aragão and Shimabukuro, 2010; Morgan et al., 2019). The extensive Amazon fires that occurred in 2019 have been linked to increased deforestation (Barlow et al., 2019).

4.5 Conclusion

We combined information on land-cover transitions and the location and timing of fires to demonstrate the close connection between fire and land-cover change in Riau, Sumatra. Fires are a component of the land management process and are used to clear vegetation from the land. We found that areas that experienced a conversion in land-cover type, experienced more frequent fire than areas that did not change land-cover. In particular, we found the greatest fire frequency in areas of secondary forest that that were changed to shrub or converted to plantation were converted to shrub or plantation. The peak in fire frequency occurred at the same time as the land-cover transition, confirming the close association between fire and land-cover change.

Frequent fire occurred in areas of shrub, which experienced fire frequency >60 times greater than primary forest and seven times greater than secondary forest. Plantation and agriculture experienced less fire than shrub, but still 17 times the rate in primary forest and double the rate of secondary forests. The conversion of natural forest to shrub, and to a lesser extent plantation and agriculture, has therefore created a fire prone landscape.

Efforts to reduce fire in Indonesia need to focus on the link between land-cover change and fire. Protecting remaining areas of natural forest, through establishing and maintaining adequately resourced protected areas, will help prevent further expansion of fire-prone shrub. Extending the plantation moratorium to include secondary forests as well as primary forests would also help reduce the conversion of natural forests and reduce the frequency of fire. Reducing the susceptibility of the landscape to fire, through restoring, rewetting and revegetating degraded shrub, particularly on peatlands, is a priority.

Bibliography

Adrianto, H.A., Spracklen, D.V. and Arnold, S.R. 2019. Relationship between Fire and Forest Cover Loss in Riau Province, Indonesia between 2001 and 2012. *Forests.* **10**(10).10.3390/f10100889

Ankerst, M., Breunig, M.M., Kriegel, H.-P., #246 and Sander, r. 1999. Optics: Ordering Points to Identify the Clustering Structure. *SIGMOD Rec.* **28**(2), pp.49-60.10.1145/304181.304187

Aragão, L.E.O.C. and Shimabukuro, Y.E. 2010. The Incidence of Fire in Amazonian Forests with Implications for Redd. *Science.* **328**(5983), p1275.10.1126/science.1186925

Barlow, J., Berenguer, E., Carmenta, R. and França, F. 2019. Clarifying Amazonia's Burning Crisis. *Global Change Biology.* **n/a**(n/a).10.1111/gcb.14872

Busch, J., Ferretti-Gallon, K., Engelmann, J., Wright, M., Austin, K.G., Stolle, F., Turubanova, S., Potapov, P.V., Margono, B.A., Hansen, M.C. and Baccini, A. 2015. Reductions in Emissions from Deforestation from Indonesia’s Moratorium on New Oil Palm, Timber, and Logging Concessions. *Proceedings of the National Academy of Sciences.* **112**(5), p1328.10.1073/pnas.1412514112

Carmenta, R., Parry, L., Blackburn, A., Vermeylen, S. and Barlow, J. 2011. Understanding Human-Fire Interactions in Tropical Forest Regions: A Case for Interdisciplinary Research across the Natural and Social Sciences. *Ecology and Society.* **16**(1).10.5751/ES-03950-160153

Chazdon, R.L., Broadbent, E.N., Rozendaal, D.M.A., Bongers, F., Zambrano, A.M.A., Aide, T.M., Balvanera, P., Becknell, J.M., Boukili, V., Brancalion, P.H.S., Craven, D., Almeida-Cortez, J.S., Cabral, G.A.L., de Jong, B., Denslow, J.S., Dent, D.H., DeWalt, S.J., Dupuy, J.M., Durán, S.M., Espírito-Santo, M.M., Fandino, M.C., César, R.G., Hall, J.S., Hernández-Stefanoni, J.L., Jakovac, C.C., Junqueira, A.B., Kennard, D., Letcher, S.G., Lohbeck, M., Martínez-Ramos, M., Massoca, P., Meave, J.A., Mesquita, R., Mora, F., Muñoz, R., Muscarella, R., Nunes, Y.R.F., Ochoa-Gaona, S., Orihuela-Belmonte, E., Peña-Claros, M., Pérez-García, E.A., Piotto, D., Powers, J.S., Rodríguez-Velazquez, J., Romero-Pérez, I.E., Ruíz, J., Saldarriaga, J.G., Sanchez-Azofeifa, A., Schwartz, N.B., Steininger, M.K., Swenson, N.G., Uriarte, M., van Breugel, M., van der Wal, H., Veloso, M.D.M., Vester, H., Vieira, I.C.G., Bentos, T.V., Williamson, G.B. and Poorter, L. 2016. Carbon Sequestration Potential of Second-Growth Forest Regeneration in the Latin American Tropics. *Science advances.* **2**(5), pp.e1501639-e1501639.10.1126/sciadv.1501639

Chazdon, R.L., Peres, C.A., Dent, D., Sheil, D., Lugo, A.E., Lamb, D., Stork, N.E. and Miller, S.E. 2009. The Potential for Species Conservation in Tropical Secondary Forests. *Conserv Biol.* **23**(6), pp.1406-1417.10.1111/j.1523-1739.2009.01338.x

Crippa, P., Castruccio, S., Archer-Nicholls, S., Lebron, G.B., Kuwata, M., Thota, A., Sumin, S., Butt, E., Wiedinmyer, C. and Spracklen, D.V. 2016. Population Exposure to Hazardous Air Quality Due to the 2015 Fires in Equatorial Asia. *Sci Rep.* **6**, p37074.10.1038/srep37074

Fanin, T. and van der Werf, G.R. 2015. Relationships between Burned Area, Forest Cover Loss, and Land Cover Change in the Brazilian Amazon Based on Satellite Data. *Biogeosciences.* **12**(20), pp.6033-6043.10.5194/bg-12-6033-2015

Field, R.D., van der Werf, G.R., Fanin, T., Fetzer, E.J., Fuller, R., Jethva, H., Levy, R., Livesey, N.J., Luo, M., Torres, O. and Worden, H.M. 2016. Indonesian Fire Activity and Smoke Pollution in 2015 Show Persistent Nonlinear Sensitivity to El Nino-Induced Drought. *Proc Natl Acad Sci U S A.* **113**(33), pp.9204-9209.10.1073/pnas.1524888113

Fornacca, D., Ren, G. and Xiao, W. 2017. Performance of Three Modis Fire Products (Mcd45a1, Mcd64a1, Mcd14ml), and Esa Fire_Cci in a Mountainous Area of Northwest Yunnan, China, Characterized by Frequent Small Fires. *Remote Sensing.* **9**(11), p1131

Gardner, T.A., Barlow, J., Chazdon, R., Ewers, R.M., Harvey, C.A., Peres, C.A. and Sodhi, N.S. 2009. Prospects for Tropical Forest Biodiversity in a Human-Modified World. *Ecol Lett.* **12**(6), pp.561-582.10.1111/j.1461-0248.2009.01294.x

Gaveau, D.L.A., Salim, M.A., Hergoualc'h, K., Locatelli, B., Sloan, S., Wooster, M., Marlier, M.E., Molidena, E., Yaen, H., DeFries, R., Verchot, L., Murdiyarso, D., Nasi, R., Holmgren, P. and Sheil, D. 2014. Major Atmospheric Emissions from Peat Fires in Southeast Asia During Non-Drought Years: Evidence from the 2013 Sumatran Fires. *Sci Rep.* **4**, p6112.10.1038/srep06112

Gaveau, D.L.A., Sheil, D., Husnayaen, Salim, M.A., Arjasakusuma, S., Ancrenaz, M., Pacheco, P. and Meijaard, E. 2016. Rapid Conversions and Avoided Deforestation: Examining Four Decades of Industrial Plantation Expansion in Borneo. *Scientific Reports.* **6**, p32017.10.1038/srep32017

https://www.nature.com/articles/srep32017#supplementary-information

Giglio, L., Schroeder, W., Hall, J.V. and Justice, C.O. 2018. *Modis Collection 6 Active Fire Product User's Guide Revision B*. NASA. Available from: http://modis-fire.umd.edu/files/MODIS_C6_Fire_User_Guide_B.pdf

Giglio, L., Schroeder, W. and Justice, C.O. 2016. The Collection 6 Modis Active Fire Detection Algorithm and Fire Products. *Remote Sensing of Environment.* **178**, pp.31-41.https://doi.org/10.1016/j.rse.2016.02.054

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., Thau, D., Stehman, S.V., Goetz, S.J., Loveland, T.R., Kommareddy, A., Egorov, A., Chini, L., Justice, C.O. and Townshend, J.R. 2013. High-Resolution Global Maps of 21st-Century Forest Cover Change. *Science.* **342**(6160), pp.850-853.10.1126/science.1244693

Harrison, M.E., Ottay, J.B., D'Arcy, L.J., Cheyne, S.M., Anggodo, Belcher, C., Cole, L., Dohong, A., Ermiasi, Y., Feldpausch, T., Gallego-Sala, A., Gunawan, A., Höing, A., Husson, S.J., Kulu, I.P., Soebagio, S.M., Mang, S., Mercado, L., Morrogh-Bernard, H.C., Page, S.E., Priyanto, R., Ripoll Capilla, B., Rowland, L., Santos, E.M., Schreer, V., Sudyana, I.N., Taman, S.B.B., Thornton, S.A., Upton, C., Wich, S.A. and van Veen, F.J.F. 2019. Tropical Forest and Peatland Conservation in Indonesia: Challenges and Directions. *People and Nature.* **n/a**(n/a).10.1002/pan3.10060

Huijnen, V., Wooster, M.J., Kaiser, J.W., Gaveau, D.L.A., Flemming, J., Parrington, M., Inness, A., Murdiyarso, D., Main, B. and van Weele, M. 2016. Fire Carbon Emissions over Maritime Southeast Asia in 2015 Largest since 1997. *Scientific Reports.* **6**, p26886.10.1038/srep26886

https://www.nature.com/articles/srep26886#supplementary-information

Kiely, L., Spracklen, D.V., Wiedinmyer, C., Conibear, L., Reddington, C.L., Archer-Nicholls, S., Lowe, D., Arnold, S.R., Knote, C., Khan, M.F., Latif, M.T., Kuwata, M., Budisulistiorini, S.H. and Syaufina, L. 2019. New Estimate of Particulate Emissions from Indonesian Peat Fires in 2015. *Atmos. Chem. Phys.* **19**(17), pp.11105-11121.10.5194/acp-19-11105-2019

Koplitz, S.N., Mickley, L.J., Marlier, M.E., Buonocore, J.J., Kim, P.S., Liu, T., Sulprizio, M.P., DeFries, R.S., Jacob, D.J., Schwartz, J., Pongsiri, M. and Myers, S.S. 2016. Public Health Impacts of the Severe Haze in Equatorial Asia in September–October 2015: Demonstration of a New Framework for Informing Fire Management Strategies to Reduce Downwind Smoke Exposure. *Environmental Research Letters.* **11**(9), p094023.10.1088/1748-9326/11/9/094023

Margono, B.A., Potapov, P.V., Turubanova, S., Stolle, F. and Hansen, M.C. 2014. Primary Forest Cover Loss in Indonesia over 2000–2012. *Nature Climate Change.* **4**(8), pp.730-735.10.1038/nclimate2277

Margono, B.A., Usman, A.B., Budiharto and Sugardiman, R.A. 2016. Indonesia's Forest Resource Monitoring. *Indonesian Journal of Geography; Vol 48, No 1 (2016): Indonesian Journal of Geography.*10.22146/ijg.12496

Marlier, M.E., DeFries, R.S., Kim, P.S., Koplitz, S.N., Jacob, D.J., Mickley, L.J. and Myers, S.S. 2015. Fire Emissions and Regional Air Quality Impacts from Fires in Oil Palm, Timber, and Logging Concessions in Indonesia. *Environmental Research Letters.* **10**(8), p085005.10.1088/1748-9326/10/8/085005

Marlier, M.E., DeFries, R.S., Voulgarakis, A., Kinney, P.L., Randerson, J.T., Shindell, D.T., Chen, Y. and Faluvegi, G. 2013. El Niño and Health Risks from Landscape Fire Emissions in Southeast Asia. *Nature climate change.* **3**, pp.131-136.10.1038/nclimate1658

Morgan, W.T., Darbyshire, E., Spracklen, D.V., Artaxo, P. and Coe, H. 2019. Non-Deforestation Drivers of Fires Are Increasingly Important Sources of Aerosol and Carbon Dioxide Emissions across Amazonia. *Scientific Reports.* **9**(1), p16975.10.1038/s41598-019-53112-6

Morton, D.C., Defries, R.S., Randerson, J.T., Giglio, L., Schroeder, W. and van der Werf, G.R. 2008. Agricultural Intensification Increases Deforestation Fire Activity in Amazonia. *Global Change Biology.* **14**(10), pp.2262-2275.10.1111/j.1365-2486.2008.01652.x

Noojipady, P., Morton, D.C., Schroeder, W., Carlson, K.M., Huang, C., Gibbs, H.K., Burns, D., Walker, N.F. and Prince, S.D. 2017. Managing Fire Risk During Drought: The Influence of Certification and El Niño on Fire-Driven Forest Conversion for Oil Palm in Southeast Asia. *Earth System Dynamics.* **8**(3), pp.749-771.10.5194/esd-8-749-2017

Page, S.E., Siegert, F., Rieley, J.O., Boehm, H.D., Jaya, A. and Limin, S. 2002. The Amount of Carbon Released from Peat and Forest Fires in Indonesia During 1997. *Nature.* **420**(6911), pp.61-65.10.1038/nature01131

Randerson, J.T., Chen, Y., van der Werf, G.R., Rogers, B.M. and Morton, D.C. 2012. Global Burned Area and Biomass Burning Emissions from Small Fires. *Journal of Geophysical Research: Biogeosciences.* **117**(G4).10.1029/2012JG002128

Reddington, C.L., Butt, E.W., Ridley, D.A., Artaxo, P., Morgan, W.T., Coe, H. and Spracklen, D.V. 2015. Air Quality and Human Health Improvements from Reductions in Deforestation-Related Fire in Brazil. *Nature Geoscience.* **8**, p768.10.1038/ngeo2535

https://www.nature.com/articles/ngeo2535#supplementary-information

Reiche, J., Verhoeven, R., Verbesselt, J., Hamunyela, E., Wielaard, N. and Herold, M. 2018. Characterizing Tropical Forest Cover Loss Using Dense Sentinel-1 Data and Active Fire Alerts. *Remote Sensing.* **10**(5).10.3390/rs10050777

Staal, A., van Nes, E.H., Hantson, S., Holmgren, M., Dekker, S.C., Pueyo, S., Xu, C. and Scheffer, M. 2018. Resilience of Tropical Tree Cover: The Roles of Climate, Fire, and Herbivory. *Global Change Biology.* **24**(11), pp.5096-5109.10.1111/gcb.14408

Sze, J.S., Jefferson and Lee, J.S.H. 2019. Evaluating the Social and Environmental Factors Behind the 2015 Extreme Fire Event in Sumatra, Indonesia. *Environmental Research Letters.* **14**(1), p015001.10.1088/1748-9326/aaee1d

Tacconi, L., Moore, P.F. and Kaimowitz, D. 2007. Fires in Tropical Forests – What Is Really the Problem? Lessons from Indonesia. *Mitigation and Adaptation Strategies for Global Change.* **12**(1), pp.55-66.10.1007/s11027-006-9040-y

Vadrevu, K.P., Csiszar, I., Ellicott, E., Giglio, L., Badarinath, K.V.S., Vermote, E. and Justice, C.O. 2013. Hotspot Analysis of Vegetation Fires and Intensity in the Indian Region. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing.* **6**(1), pp.224-238.10.1109/jstars.2012.2210699

Vadrevu, K.P., Lasko, K., Giglio, L., Schroeder, W., Biswas, S. and Justice, C.O. 2019. Trends in Vegetation Fires in South and Southeast Asian Countries. *Scientific Reports.* **9**(1), p7422.10.1038/s41598-019-43940-x

Vadrevu, K.P., Ohara, T. and Justice, C.O. 2017. Land Cover, Land Use Changes and Air Pollution in Asia: A Synthesis. *Environmental Research Letters.* **12**(12), p120201.10.1088/1748-9326/aa9c5d

van Marle, M.J.E., Field, R.D., van der Werf, G.R., Estrada de Wagt, I.A., Houghton, R.A., Rizzo, L.V., Artaxo, P. and Tsigaridis, K. 2017. Fire and Deforestation Dynamics in Amazonia (1973–2014). *Global Biogeochemical Cycles.* **31**(1), pp.24-38.10.1002/2016GB005445

Chapter 5

Fire Hotspot Occurrence Modelling Based On Historical Hotspot, Tree Cover Loss And Land Cover Transition Between 2011 and 2019

Abstract : The impact of fires on vegetation is influenced by land use and land cover. Therefore, information on the distribution of fire occurrence related to the changing condition of land over time is also essential to identify high risk fire areas, fire controlling actions and for evaluation of fire prevention programs. In this research, we try to develop a formula to estimate hotspot occurences between 2011-2019 in Riau Province, Indonesia based on antecedent hotspot, tree cover loss and land cover transition. We choose hotspot count (number of hotspot between 2011-2019), hotspot mean (hotspot count km^{-2} year^{-1}) and hotspot class as target variables. Several methods are chosen to fit the target class, i.e. Linear Model (LM), Generalized Linear Model (LM) and Geographically Weighted Regression (GWR). We found no model capable of predicting hotspots with currently used datasets and spatio-temporal scale. Whenever available, we suggest analysis should include a time series of plantation concession maps with information on their status such as date of establishment, change permit or closure and condition of vegetation cover condition. In addition, we recommend focusing analysis on the transition of secondary forest into plantation or shrub.

5.1 Introduction

How natural and human forces shaped present-day environments and ecological patterns could be understood by reconstructing the past (Foster, 2002). For example, land use / land cover change over time and associated disturbances may leave visible marks on the landscape (Turner, 2005). Globally, large scale forest deforestation mainly occurs as edge and patch cases (Riitters, K. et al., 2000). Furthermore, extensive edge effects have likely forced ecological processes on Continental United States forested land (Riitters, K et al., 2002). Global forest area experienced 1.71 million km^2 (3.2 %) net loss from 2000 to 2012, which relate to 3.76 million km^2 (9.9 %) of forest interior area net loss (Riitters, K. et al., 2015). Indonesia experienced 60 200 km^2 of primary forest loss between 2000 and 2012 (Margono et al., 2014). Industrial concessions related to almost half of forest loss in

Indonesia between 2000 and 2010 (Abood et al., 2015). They reported that the largest forest loss were in fiber plantation (~1.9 Mha) and logging concession (~1.8 Mha), and oil palm accounted for ~1 Mha forest loss.

Fire is a major disturbance influencing vegetation composition, structure and dynamics (Thonicke et al., 2001). Active fire detection is an important method to characterize the seasonality, timing and interannual variations in biomass burning (Eva and Lambin, 1998). The impact of biomass burning on the modification in vegetation cover and the mosaic of land use can be assessed at the landscape scale. However, fires are not always the cause of land cover change and fires are not always a strong indicator for deforestation concentration area (Eva and Lambin, 2000). The impact of fires on vegetation is controlled mainly by land use.

The connection between land use transition and fire events has been a critical question for some time (Dennis, 1999). A review in Kalimantan emphasizes that fire has a notable role both in the creation and destruction of secondary forest (Dennis et al., 2001). A study in Riau, Indonesia (Adrianto et al., 2019) shows the role of fire in the deforestation process, with fire frequently occurring around the time of land cover change. Furthermore, the majority of fire is associated with the transition of secondary forest to shrub and plantation (Adrianto et al., 2020). Since reducing fires is essential to incorporate into peatland restoration and conservation planning (Harrison et al., 2019), then modelling fire hotspot occurrences is crucial. Research on the temporal distribution of fire occurrences is needed to anticipate future fires and have been developed based on meteorological variables such as weather, weather indices and fuel moisture (Plucinski, 2012; Spessa et al., 2015). Information on the spatial distribution of fire occurrence is also essential to identify high risk fire areas, fire controlling actions and evaluation of fire prevention programs.

Methods for analysis, modelling and application of fire occurrence in Indonesia

Table 5.1 presents a summary of the methods used in previous studies for analysis, modelling and application of fire occurrence in Indonesia. Map overlay / superimpose has been used for a long time to study affecting factors on forest fire such as weather (Anderson and Bowen, 2000; Langner and Siegert, 2009) and land use / land cover (Ardiansyah et al., 2017; Bowen et al., 2001; Gaveau et al., 2014; Langner et al., 2007). Some studies have combined remote sensing data with social surveys or ethnographic methods (Applegate et al., 2001; Dennis et al., 2005) or as multiscale analysis (Siegert et al., 2001). In addition, to measure fire hotspot in certain locations, a study had been done to detect neighbourhood fire pixels (Cattau et al., 2016a). Hotspots as binary (fire / non-fire) events can be analysed using logistic regression (Sitanggang et al., 2013; Sumarga, 2017) and its multivariate extension (Stolle et al., 2003; Stolle and Lambin, 2003). Furthermore, if the independent variable may have several “segments” then multiple linear models are suitable (Field and Shen, 2008; Field et al., 2016; Field et al., 2009; Nikonovas et al., 2019). Other studies Cattau et al. (2016b); (Gaveau et al., 2009; Gaveau et al., 2013) demonstrate that propensity score matching is beneficial. Other approaches are classification (Gaveau et al., 2007) to assign datasets a certain label and clustering (Kirana et al., 2016; Prasetyo et al., 2016) when the number of groups in the dataset is not predetermined. Classification methods based on the splitting rule are known as decision tree methods (Sitanggang and Ismail, 2011; Sloan et al., 2017). Interaction of fire hotspots with covariates such as time series fluctuation can be explored using cross correlation (Cahyono et al., 2013; Fuller and Murphy, 2006). The time order of hotspot events is important in sequence pattern analysis (Sitanggang et al., 2018; Syaufina and Sitanggang, 2018). Since there is a chance that the distribution of fire hotspot varies spatially, then geographically weighted regression can be used (Van der Laan et al., 2014).

Various factors influenced land fires in Indonesia

Previous research summarised in **Table 5.1** suggests various factors influenced land fires in Indonesia. There is evidence that fires are influenced by Southern Oscillation Index (SOI) and Nino 3.4 index (Fuller and Murphy, 2006). Furthermore, Cahyono et al. (2013) mentioned that precipitation and SOI are the best predictor for fire in the following two months. Also, 4-months of low precipitation will increase fire risk (Field and Shen, 2008) more specifically during prolonged periods with less than 4 mm/d of precipitation (Field et al., 2016). As a result of prolonged droughts related to El Niño , fire-affected area in Borneo was on average triple that during normal weather (Langner and Siegert, 2009). In another study, fire frequency increased when rainfall fell below 200 mm per month (Sloan et al., 2017). Another important climatic oscillation in the region is the Indian Ocean Dipole (IOD) which expresses anomalously low sea surface temperature off Sumatra and high sea surface temperature in the western Indian Ocean (Saji et al., 1999). Previous studies found that the IOD might also play a role in modulating Indonesian fire events by association with El Niño (Fanin and van der Werf, 2017; Field et al., 2009) Later, Pan et al. (2018) found that during the Eastern Pacific El Niño event,the strong IOD in 2006 contributes to the drier conditions and thus more intensive fire activities.

Alencar et al. (2011) highlight that climate conditions and droughts affect temporal variability of forest fire such as fire frequencies and the variation in fire return intervals (FRI). In Kalimantan and Sumatra, the FRI in peatlands were 28 and 45 years while the FRI in non-forest areas were 13 years and 40 years respectively, suggesting a more prevalent repeat fire in Kalimantan where trees are replaced by shrubs and other vegetation (Vetrita and Cochrane, 2020). Fanin and van der Werf (2017) found that 120 days of rainfall accumulation prior to active fires had the highest coefficient of determination with annual fire intensity in Sumatra and Kalimantan. Furthermore, they reveal that most fires in southern Sumatra and Kalimantan occurred between August and October while northern Sumatra had a short fire season in February and a longer one between June and August.

It is also important to consider the influence of human actions on fire. Bowen et al. (2001) reports that humans caused all vegetation fires in Indonesia. For example, fire is directly induced by land clearing, land disputes, escaped fires and resource extraction (Applegate et al., 2001; Dennis et al., 2005). Ardiansyah et al. (2017) found almost one-third burned area in South Sumatra occurred outside licensed area whereas fire activity in concession spreads to forest plantation (30%) and oil-palm (19%).

It is clear that land and forest fires involve complex processes influenced both by weather and human activity. There are connections between land-cover and weather, with different land cover types showing different fire weather characteristics (Nikonovas et al., 2019). Similarly, Field et al. (2009)

shows that the variation of land use patterns and population density results in extensive fires occurring earlier in Sumatra (1960's) compared to Kalimantan (1980's).

The link between land use and weather is also perceived in dry years (1997), when plantation and logging concession only gave a minor effect on fire increment but the areas not yet used by large-scale landowners were the most vulnerable area (Stolle and Lambin, 2003). On contrary in the 1996, 1998, 1999 and 2000 non-ENSO years, a few hundreds of thousand hectares of burned area represented repeat clearance by smallholder farmers while a few tens of thousand of hectares were related to the opening-up of new land by estate crop companies (Anderson and Bowen, 2000). A study in Riau in a wet year (2013) shows that 163 000 hectares were burned after two months of dry weather, with 81% of burned lands classified as "non-forest" and 57% of burned ‘non-forest’ areas consisting of scrub and exposed soil, with stumps, downed trunks and branches (Gaveau et al., 2014). In Jambi province, regardless of the weather, fire seems to occur every year in peat land covered by bush or disturbed secondary forest (Prasetyo et al., 2016). In that province, fires were suppressed in operational concessions, but occur in logged-over forests and forests allocated to production but not yet under use (Stolle et al., 2003). Siegert et al. (2001) mentioned that recently logged forest were more affected by fire than intact forest or long-been logged forest.

As the actor of land use / land cover change, how companies manage their concession areas is also crucial. Cattau et al. (2016a) found limited evidence of fires occurring on or escaping from oil palm concessions and settlements. In the case of oil palm plantation certification, when fire risk is low (i.e non-peatland in wetter years), fire activity is significantly lower on RSPO certified concessions than non-RSPO certified concessions. On the other hand, fire activity is much higher on RSPO certified concession in high risk condition such as on non-peatlands in dry years or on peatlands (Cattau et al., 2016b). Recently, Indonesia RSPO certified oil palm during the 2009 and 2015 El Nino events accounted for 75% and 66% lower fire activity than noncertified plantations (Noojipady et al., 2017).

Spatial relationship of fire occurrences

The spatial relationship between fire and certain objects may provide key indication to fire occurrences. For instance, fires in Borneo are prevalent in the surroundings of oil palm with peaks in fire occurrence at 3-5 km distance (Sloan et al., 2017). In a part of Riau province, plantation area located more than 4.5 km from a river are more susceptible to fire (Sitanggang and Ismail, 2011). The 5 km buffer zone from the forest edge is crucial, with most deforestation and forest fires taking place there (Langner et al., 2007). A study in Central Kalimantan found that the probability of fire occurrences increases as distance from roads and rivers increases (Sumarga, 2017). In North and East Kalimantan, fire probability is affected by distance to nearest fire and land allocation zoning (Van der Laan et al., 2014). Sitanggang et al. (2018) discovered that the majority of actual fire spots were identified from fire hotspots that appear in consecutive hotspots within one kilometre buffer of burned area.

Fortunately, natural forest timber concessions and protected areas (PA) were capable of preventing forest cover loss in Kalimantan (Gaveau et al., 2013). A different situation took place in Southwest Sumatra where PAs successfully reduced large-scale mechanized logging and enhanced forest regrowth, but they were unsuccessful at avoiding agricultural encroachments (Gaveau et al., 2007). At broader scales, Sumatran PAs have lower deforestation rates than unprotected areas, however they did not stop deforestation and logging inside them (Gaveau et al., 2009).

Another relevant factor in relation to fire is soil type, especially peat land. As an example, the proportion of hotspots that occurred in Sumatra’s deep peat (201-400 cm thickness) doubled from 16% in 2001-2006 up to 30% in 2007-2014 (Kirana et al., 2016). More specifically, in Rokan Hilir District, Riau Province, Saprist is the only significant peatland type affecting the hotspot occurrences (Sitanggang et al., 2013). A study in Kalimantan suggests that actual fire in peatland is indicated by three consecutive days of hotspot occurrences (Syaufina and Sitanggang, 2018).

According to variables listed in Table 5.1, we found no research which included land cover transitions to quantify fire occurrences. In this research, we try to develop a formula to predict the number of hotspot between 2011-2019 as a spatial map of land risk in Riau Province, Indonesia, using previous years attributes such as hotspot, tree cover loss and land cover transition.

Table 5.1 Example of Research on Forest Fire Modelling and Land Cover Dynamics in Indonesia

Reference	Domain	Primary Method	Variables used	Significant Finding
(Adrianto et al., 2019)	Riau Province (2011-2012)	Map overlay	MODIS fire hotspots, tree-cover loss, peatland map, protected areas, and concessions	Regions with forest loss experienced six times as many fire hotspots compared to regions with no forest loss. Forest loss and maximum fire frequency occurred within the same year, or one year apart, in 70% of the 1 km^2 cells experiencing both forest loss and fire.
(Adrianto et al., 2020)	Riau Province (1990-2017)	Land-cover transitions matrices	land-cover, MODIS fire hotspot	Fire is closely connected to land-cover change, and that the majority of fire is associated with the transition of secondary forest to shrub and plantation.
(Anderson and Bowen, 2000)	Sumatra (1996-2000)	Map overlay	SPOT imagery, NOAA fire occurrence, oil palm report, field visit	In the 1996, 1998, 1999 and 2000 non-ENSO years, a few hundred thousand hectares of burned area were represent repeat clearance by smallholder farmers while a few tens of thousand of hectares were related to the opening-up of new land by estate crop companies.
(Applegate et al., 2001)	Sumatra and Kalimantan (1998-2000)	RS and GIS with on-the-ground participatory mapping	Social surveys and remote sensing imageries	Fire directly induced by land clearing, land disputes, escaped fires and resource extraction

Table 5.1 (continue)

Reference	Domain	Primary Method	Variables used	Significant Finding
(Ardiansyah et al., 2017)	South Sumatra (2015)	Map overlay	MODIS fire, concession map, forest area map, land cover map, peat soil map	Almost one-third burned area occurred outside licensed area whereas fire activity in concession spreads to forest plantation (30%) and oil palm (19%)
(Bowen et al., 2001)	Sumatra (1996-1998)	Map overlay	Hotspot location, land use map	Human activity caused all vegetation fires in Indonesia
(Cahyono et al., 2013)	Riau Province (2001-2010)	Cross correlation	Southern Oscillation Index (SOI), MODIS Fire Hotspot, precipitation	Precipitation and SOI are the best predictor for the next two months fire.
(Cattau et al., 2016a)	Central Kalimantan (2000-2010)	neighborhood-pixel fire detections	MODIS Active Fire product, LULC classes (oil palm concessions, forest, and non-forest)	The statement that fires occurring on or escaping from oil palm concessions and settlements, has limited evidence.
(Cattau et al., 2016b)	Sumatra and Kalimantan (2012-2015)	Propensity score matching	Oil palm concession location, density of fire detections and fire ignitions (from MODIS Active Fire), peatland map, mean road density	When fire risk is low (i.e non-peatland in wetter years), fire activity is significantly lower on RSPO certified concessions than non-RSPO certified concessions. On the other hand, fire activity is much higher on RSPO certified concession in high risk condition such as on non-peatlands in dry years or on peatlands

Table 5.1 (continue)

Reference	Domain	Primary Method	Variables used	Significant Finding
(Dennis et al., 2005)	Kalimantan and Sumatra (1985-1998)	Ethnographic methods	LANDSAT and SPOT remote sensing analysis, NOAA AVHRR active fires, interview, participatory sketch mapping and baseline information	The most important fire sources are : land clearing, accidental or escaped fire, land tenure or land-use conflict, and resource extraction
(Field and Shen, 2008)	Sumatra, Kalimantan and Papua (1997-2006)	piecewise linear regression	Biomass burning emissions (GFED), fire occurrence and area burned (ATSR, TRMM, MODIS), Climatic Indices, Precipitation (PRECL), soil moisture (SOILM), surface air temperature (NCEP-NCAR)	4-months of low precipitation will increase fire risk in Sumatra, Kalimantan and Papua with threshold respectively are 350 mm, 600 mm and 900 mm.
(Field et al., 2009)	Sumatra and Kalimantan (1960-2006)	piecewise linear regression	Land cover, GFED TPM emission, precipitation	Extensive fires have occurred earlier in Sumatra (1960's) than Kalimantan (1980's) because of variation of land use patterns and population density.
(Field et al., 2016)	Sumatra and Kalimantan (2015)	piecewise linear regression	MODIS active fire detections, tropospheric pollution, airport visibility records, and precipitation estimates from satellites and rain gauges.	Fire and pollution increased rapidly during prolonged periods with less than 4mm/d of precipitation

Table 5.1 (continue)

Reference	Domain	Primary Method	Variables used	Significant Finding
(Fuller and Murphy, 2006)	Insular Southeast Asia - 100◦ E–140◦ E longitude and 15.5◦ S–7.5◦ N (1997-2001)	autocorrelation (ACF) and cross correlation functions (CCF)	Fire dataset (ATSR) , population density, elevation, MacKinnon land cover type, and percent tree cover	Fires were influenced by Southern Oscillation Index and Nino 3.4 index in forested land-cover types
(Gaveau et al., 2007)	Southwest Sumatra (1972-2002)	gaussian Maximum Likelihood Classification	Forest types, topography, forest fragmentation, forest regrowth, protected area boundary	PAs successfully reduced large-scale mechanized logging and made 8610 ha forest regrowth, but unsuccessful to avoid agricultural encroachments
(Gaveau et al., 2013)	Kalimantan (2000-2010)	propensity score matching	Tree cover loss, Land use maps	natural forest timber concessions and PAs were capable of preventing forest cover loss
(Gaveau et al., 2014)	Riau Province (2013)	Map overlay	Daily fire hotspots, burned area, rainfall, FRP, LANDSAT scene, UAV-based vegetation map, Singapore's 24-hour Pollutant Standards Index (PSI)	After two months of dry weather in a wet year (2013), 163 000 hectares were burned in Riau. 81% of burned lands were classified as "non-forest". Furthermore, 57% of burned 'non-forest' areas consisted of scrub and exposed soil, with stumps, downed trunks and branches.

Table 5.1 (continue)

Reference	Domain	Primary Method	Variables used	Significant Finding
(Gaveau et al., 2009)	Sumatra (1990-2000)	propensity score matching, regression	Protected Area boundary, accessibility, soil and forest types	Sumatran PAs have lower deforestation rates than unprotected areas, however they did not stop deforestation and logging inside them
(Kirana et al., 2016)	Sumatera (2001- 2014)	Kulldorf' s scan statistic	FIRMS MODIS Fire/Hotspot data, peat land map	The proportion of hotspot occurred in deep peat (201-400 cm thickness) doubled from 16% in 2001-2006 up to 30% in 2007-2014
(Langner and Siegert, 2009)	Borneo (1997-2006)	Map Superimpose	Land cover classification, active fire locations	During prolonged droughts due to El Nino, fire-affected area in Borneo was on average triple that during normal weather and in the Indonesian part of Borneo was five times larger.
(Langner et al., 2007)	Borneo (2003-2005)	Map Superimpose	Land cover classification, active fire locations	The 5km buffer zone from forest edge is crucial and is where most deforestation and forest fire took place there.
(Nikonovas et al., 2019)	Indonesia (2002 – 2018)	Piecewise regression	MODIS active fire, Fire Weather Index (FWI), Drought Code (DC), peatland land cover maps, forest cover loss	Different land cover types show different fire weather characteristics which are useful for fire early warning system

Table 5.1 (continue)

Reference	Domain	Primary Method	Variables used	Significant Finding
(Noojipady et al., 2017)	Indonesia (2002-2015)	Time series map superimpose	Oil palm plantation boundary, MODIS MCD14ML active fire, forest cover, forest change	Indonesia RSPO certified oil palm during the 2009 and 2015 El Nino events accounted for 75% and 66% lower fire activity than noncertified plantations
(Prasetyo et al., 2016)	Jambi Province (2000-2015)	Getis-Ord-Gi* statistics	MODIS active fire, land use, land cover	Regardless of the weather, fire seems to occur every year in peat land where covered by bush or disturbed secondary forest one year before the events
(Siegert et al., 2001)	East Kalimantan (1997-1998)	RS multiscale analysis	AVHRR hotspot, natural forest concessions, plantations, industrial timber crops, protected forests, radar-based fire-impact map	Recently logged forest were more affected by fire than intact forest or long-been logged forest
(Sitanggang et al., 2018)	Central Kalimantan and West Kalimantan Province (2014-2015).	Sequential pattern	Fire hotspot, burned area, peatland map, Landsat imagery	Majority of actual fire spots were identified from fire hotspots that appear in consecutive hotspots within one kilometer buffer of burned area

Table 5.1 (continue)

Reference	Domain	Primary Method	Variables used	Significant Finding
(Sitanggang and Ismail, 2011)	Rokan Hilir District, Riau Province (2008).	Decision Tree	Location of hotspot occurrences, location of city centers, road and river networks, land cover types.	Plantation area which located more than 4.5 km to river are more susceptible to fire.
(Sitanggang et al., 2013)	Rokan Hilir District, Riau Province (2008).	Logistic Regression	Location of hotspot occurrences, location of city centers, road and river networks, land cover types, Income source, precipitation, screen temperature, windspeed, peatland type and depth	Peatland type of Saprist is the only significant factor affecting the hotspot occurrences
(Sloan et al., 2017)	Borneo (1982-2002)	Random-forest	AVHRR GAC, oil palm and timber plantation extent and proximity, logging intensity and proximity, human settlement, climate, forest and peatland condition, and time	Fire frequency increased when rainfall fell below 200 mm per month and prevalent in surroundings of oil palm peaking at 3-5 km distance.
(Stolle and Lambin, 2003)	Sumatra (1997-1999)	multivariate logistic regression	presence of undisturbed forests, elevation, land allocation to production or conversion areas, presence of plantations, distance from roads, smallholder area	In the dry year (1997), fires were more likely to occur in plantation and logging concession only gave a minor effect on fire increment. Furthermore, the areas not yet used by large-scale landowners were the most vulnerable area.

Table 5.1 (continue)

Reference	Domain	Primary Method	Variables used	Significant Finding
(Stolle et al., 2003)	Jambi Province (1992-1993)	multivariate logistic regression	land use, land use zoning, accessibility, land cover, climate, elevation, suitability for specific tree crops, presence of transmigration projects and land allocation to specific land uses	Both large- and small-holder contributed to fire occurrence. Fires were suppressed by in the time of concessions operation, but occur in logged-over forests and forests allocated to production but not yet under use.
(Sumarga, 2017)	Central Kalimantan (2015)	Logistic regression	land uses, land status, distance to road, distance to settlement, distance to river, elevation, slope, peatland, hotspot occurrences	Areas with high risk of fire are found on peatland covered by shrubs or oil palm with high reachability (low elevation, steep slope) but far from roads and rivers
(Syaufina and Sitanggang, 2018)	Kalimantan (2015)	Sequential pattern	Fire hotspot, peatland map	Actual fire in peatland is indicated by three consecutive days of hotspot occurrences.
(Van der Laan et al., 2014)	North and East Kalimantan (2000-2008)	Geographically weighted regression	Altitude, slope, land allocation zoning, soil type, and distance to the nearest fire, road, river and city	The location distribution of aboveground biomass highly influenced by altitude, distance to nearest fire and land allocation zoning.

5.2 Data and Method

In this research, all base datasets are overlaid and represented as 1 km^2 cells (Figure 2.16). The 2011-2019 hotspot dataset was obtained from FIRMS and hotspots with minimum 80% confidence level were selected. We also used the land cover dataset from the Indonesian Ministry of Forestry and Environment which is available annually for 2011-2017. The land cover dataset has 23 different land-cover classifications (Table 2.6). Other datasets used are tree cover loss from Hansen_GFC-2017-v1.5 dataset which provides the Tree Cover Loss layer (30 m) aggregated into 1 km using the SUM function (Figure 2.22). The same process also applied to the Loss Year layer using the MODAL function. Also we use land system from Global Forest Watch which gives the distribution of peat and non-peat areas.

There are several ways to characterize fire behaviour. Numata et al. (2011) mentioned how many times certain areas burned (once, twice, etc) as fire frequency and identify fire severity classes (e.g. low, moderate and high). Langner and Siegert (2009) use annual fire-affected areas where one single hotspot pixel can be affected by a single fire or more than one fire. Miettinen et al. (2010) defines hotspot density as number of fire detections per 1000 km^2 and hotspot proximity value as the average number of active fires detected within a 5-km radius from any given hotspot. Barbosa and Fearnside (2005) adopt the mean frequency of fire, which refers to number of years for an area to burn again.

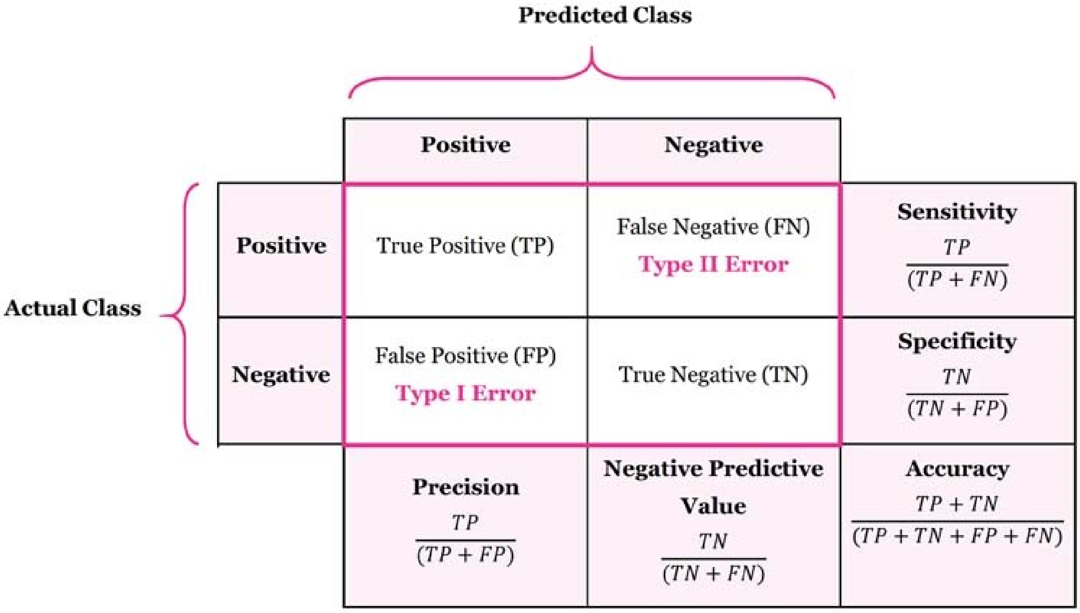
We choose the following target variables to indicate fire hotspot occurrence:

Hotspot_Count : total number of hotspots in a cell between 2011 and 2019.

Hotspot_Mean : Hotspot_Count/unit area/9 years (km^{-2} year^{-1}).

Hotspot_Class : "No Hotspot","1","2-5", "6-10" and "More than 10".

Several methods are chosen to fit the target class, i.e. Linear Model (LM) or Generalized Linear Model (GLM) for numeric and Decision Tree (DT) or Random Forest (RF) for categoric. To accommodate the spatial variation of target variables, we also apply Geographically Weighted Regression (GWR). Firstly, our analysis are at 1 km^2 resolution where hotspot metrics (count, mean and class) are predicted based on land cover label for each year only. Later, hotspot state is modelled using tree cover loss and land system. Due to a small fraction of 1 km^2 land cover transition cells with repeated fire then it is hard to forecast fire/non-fire status of certain cells in specific year in this spatial scale. So finally we try to model fire risk using land cover transition in 5 km x 5 km scale. Figure 5.1 shows metrics to measure goodness of models with categoric target such as SVM and DT.



		Predicted Class		
		Positive	**Negative**	
Actual Class	**Positive**	True Positive (TP)	False Negative (FN) **Type II Error**	**Sensitivity** $\frac{TP}{(TP+FN)}$
	Negative	False Positive (FP) **Type I Error**	True Negative (TN)	**Specificity** $\frac{TN}{(TN+FP)}$
		Precision $\frac{TP}{(TP+FP)}$	**Negative Predictive Value** $\frac{TN}{(TN+FN)}$	**Accuracy** $\frac{TP+TN}{(TP+TN+FP+FN)}$

Figure 5.1 Prediction Goodness Measure.

On the other hand, models with numeric target such as GLM, SVR and LR can be evaluated using Root Mean Square Error (RMSE), R-squared and Adjusted R-Squared metrics:

$$R^2 = 1 - \frac{SS_{residuals}}{SS_{total}}$$

$$\text{Adjusted R}^2 = 1 - \frac{SS_{residuals} \big/ (n-K)}{SS_{total} \big/ (n-1)}$$

Brief descriptions for schemes used in this research are explained in the next sections. Note that in the following models, the “PL” prefix of variables means *Penutupan Lahan* (Land cover).

5.2.1 Predict hotspot count using tree cover loss and land system (HotspotCount_LossPeat-LM)

This scheme predicts hotspot count in 25 km^2 cells during 2011-2019 using tree cover loss and land system, with interaction among predictors. Tree cover loss is represented as a percentage and land system attribute values are peat or non-peat.

The formula of this model is:

```
HotspotCount.withInteration.Loss_pct_Landsystem.lm <-
lm(HotspotCount~Loss_pct * Landsystem, data =
Landsystem_PL_hotspot_loss.SelectedTransOverall.25km2.dataframe)
```

5.2.2 Predict hotspot mean using tree cover loss and land system (HotspotMean_LossPeat-LM)

This scheme predicts hotspot mean in 25 km^2 cells during 2011-2019 using tree cover loss and land system, both as additive (without interaction) and with interaction among predictors. Tree cover loss is represented as a percentage and land system attribute values are peat or non-peat.

The formula of these model are:

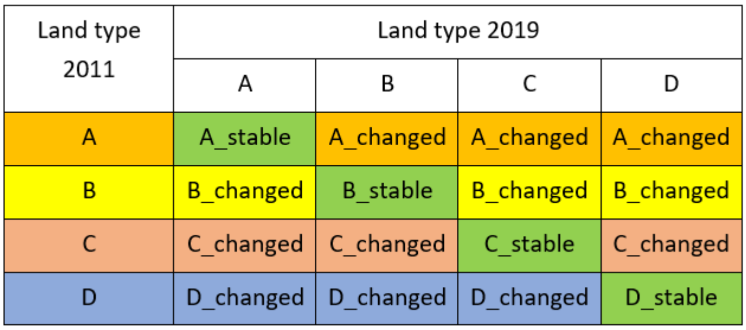
```
Hotspot_perkm2_peryear.Additive.Loss_pct_Landsystem.lm <-
lm(Hotspot_perkm2_peryear~Loss_pct+Landsystem, data =
Landsystem_PL_hotspot_loss.SelectedTransOverall.25km2.dataframe)
```

```
Hotspot_perkm2_peryear.withInteration.Loss_pct_Landsystem.lm <-
lm(Hotspot_perkm2_peryear~Loss_pct*Landsystem, data =
Landsystem_PL_hotspot_loss.SelectedTransOverall.25km2.dataframe)
```

5.2.3 Predict hotspot count using land cover transition (HotspotCount_Landcover_Transition-GLM)

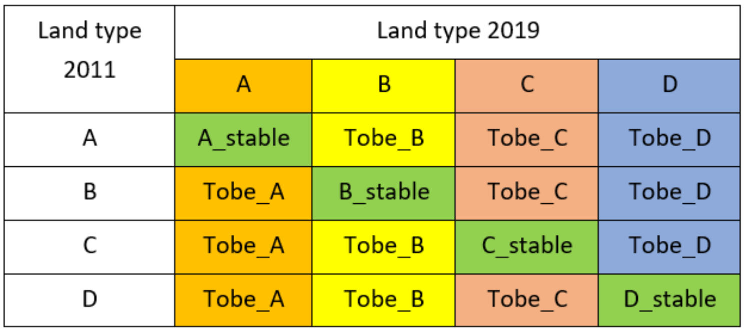
In this scheme we use GLM model with Poisson link to predict Hotspot Count based on landcover dynamics in 25km^2 cells. Land cover dynamics represented as the pair matching of major land cover types in 2011 and 2019 (AGR, PDF, PLT, PSF, SDF, SRB and SSF). In this 25 km^2 aggregate unit, we use the number of 1 km^2 cells which have stable land cover type during 2011-2019 and the number of cells which had been transformed. Land cover modification was measured as the number of cells in 2011 which had changed in 2019 (“changed”) and the number of cells in 2019 which come from another land cover change in 2011 (“tobe”).

Figure 5.2 shows the land transformation which focused on the beginning of transition while Figure 5.3 pays more attention on land cover in the end of transition.



Land type 2011	Land type 2019			
	A	B	C	D
A	A_stable	A_changed	A_changed	A_changed
B	B_changed	B_stable	B_changed	B_changed
C	C_changed	C_changed	C_stable	C_changed
D	D_changed	D_changed	D_changed	D_stable

Figure 5.2 Begin of transition oriented.



Land type 2011	Land type 2019			
	A	B	C	D
A	A_stable	Tobe_B	Tobe_C	Tobe_D
B	Tobe_A	B_stable	Tobe_C	Tobe_D
C	Tobe_A	Tobe_B	C_stable	Tobe_D
D	Tobe_A	Tobe_B	Tobe_C	D_stable

Figure 5.3 End of transition oriented.

Begin of transition oriented :

```
HotspotCount2011_2019.Landcover_stable_change.25km2.poisson <-
glm(HotspotCount ~ AGR_stable  + PDF_stable + PLT_stable  +
PSF_stable  + SDF_stable  + SRB_stable + SSF_stable + AGR_changed  +
PDF_changed + PLT_changed  + PSF_changed  + SDF_changed  +
SRB_changed + SSF_changed, data =
PL_hotspot_loss.SelectedTransOverall.25km2.TRAINING  ,
family=poisson())
```

End of transition oriented :

```
HotspotCount2011_2019.Landcover_stable_change.25km2.poisson <-
glm(HotspotCount ~ AGR_stable + PDF_stable + PLT_stable +  PSF_stable
+ SDF_stable + SRB_stable + SSF_stable + AGR_tobe +  PDF_tobe +
PLT_tobe + PSF_tobe + SDF_tobe + SRB_tobe + SSF_tobe, family =
poisson(), data = PL_hotspot_loss.SelectedTransOverall.25km2.TRAINING)
```

5.2.4 Predict hotspot count based on landcover dynamics (HotspotCount_Landcover_Transition_LossPeat-GLM)

Here, a GLM model with Poisson link is used to predict Hotspot Count based on landcover dynamics in 25 km^2 cells as well as tree cover loss and land system. Land cover transition is represented as pair matching of major land cover types in 2011 and 2019 (AGR, PDF, PLT, PSF, SDF, SRB and SSF) weighted by hotspot density. Numbers of each land cover change pair in 1 km^2 cells are weighted by hotspot density (number of hotspot / land transition area). Furthermore, the score for certain land cover in 2011 changing to any land cover in 2019 are summed up and gives the potential risk of each land cover type modification. The risk values are then multiplied by the fraction of total hotspot during 2011-2019 for each land cover type in 2019.

The formula of this scheme is :

```
HotspotCount_Landcover_Transition_LossPeat  <- glm(HotspotCount ~
HotspotDensity.weighted * Loss_pct*Landsystem, data =
Cells_with_.SelectedTransOverall_JOIN_HotspotDensityWeight.sf,
family=poisson())
```

5.2.5 Geographically Weighted Regression (GWR)

The prediction of hotspot count based on the number of 1 km^2 cells with tree cover loss (ranges 0-25) and land system (peat/non-peat) is applied using geographically weighted regression.

The bandwidth for geographically weighted regression of above model is found by gwr.sel function:

```
GWRbandwidth_Interaction <- gwr.sel(HotspotCount ~ LossCount *
Landsystem, data=Cells_with_.SelectedTransOverall.sp, adapt =TRUE
```

Then the GWR model is:

```
gwr.model = gwr(HotspotCount ~ LossCount * Landsystem,
data=Cells_with_.SelectedTransOverall.sp, adapt=
GWRbandwidth_Interaction, hatmatrix=TRUE, se.fit=TRUE)
```

5.3 Results

Figure 5.4 shows the hotspot mean density during 2011 to 2019 (km^{-2} year^{-1}) demonstrating the spatial clustering of fire occurrence. Figure 5.5 displays the distribution of hotspot counts for cells with at least one hotspot during this period. While more than half of cells contain only one fire hotspot event, a small number of them have six fire hotspots or more.

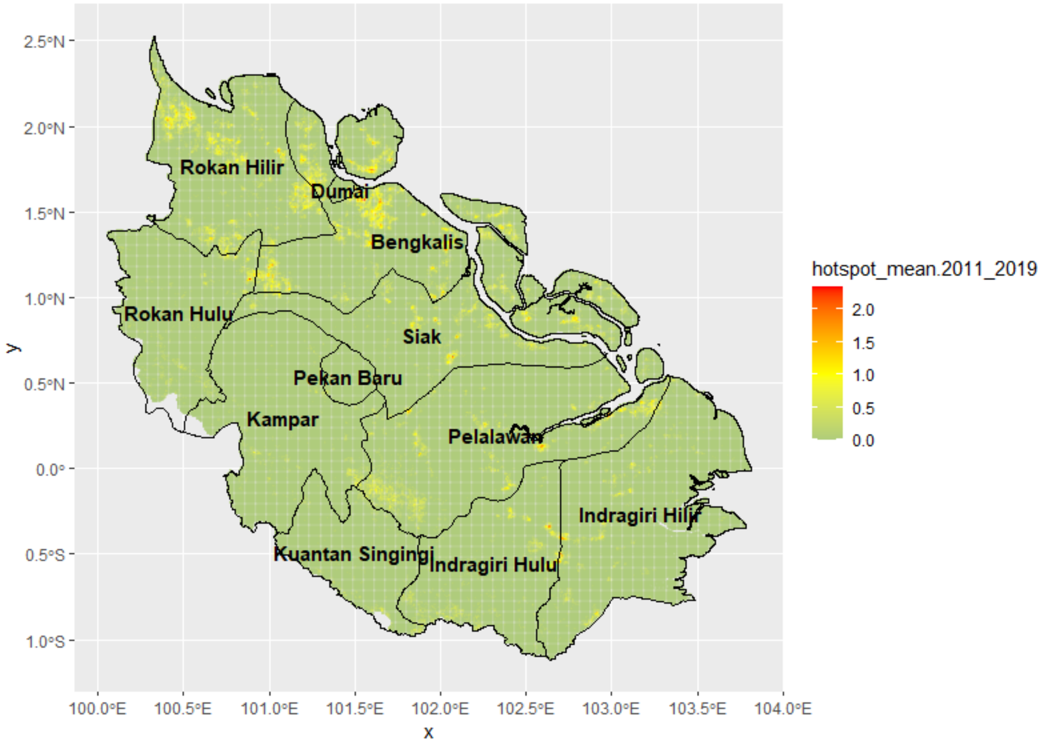


Figure 5.4 Average hotspot density (km^{-2} year^{-1}) during 2011-2019.

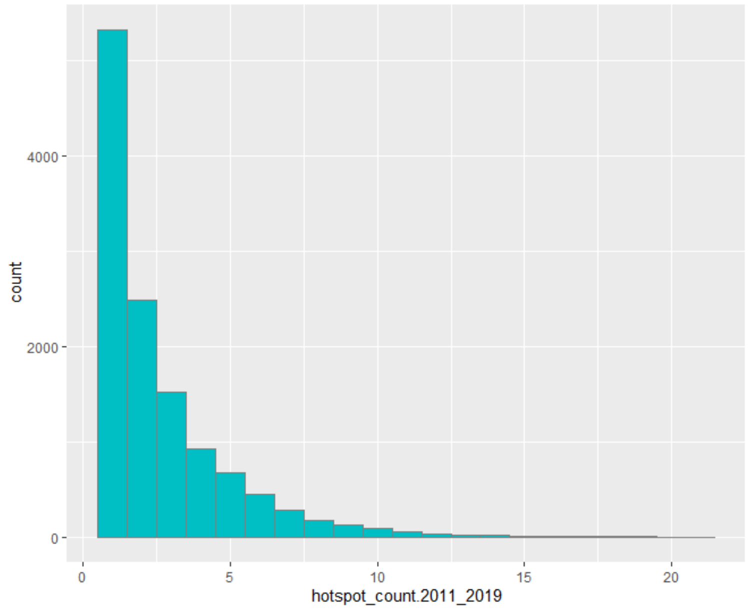


Figure 5.5 Hotspot count (2011-2019).

When processing the land-cover map from Ministry of Environment and Forestry, we assumed no further change in land cover for 2018-2019 and reclassified it as nine grouped land-cover classes, namely primary dryland forest (PDF), primary peat swamp forest (PSF), secondary dryland forest (SDF), secondary peat swamp forest (SSF), plantation (PLT), shrub (SRB), water (WTR), agriculture (AGR) and urban (URB). In this grouped classification, peat swamp forest consists of swamp forest and mangrove forest, plantation contains plantation forest and estate crop, and shrub consists of non-forest dry shrub, wet shrub/swampy shrub, savanna/grasses, and bare ground/bare soil (Table 2.7).

Figure 5.6 and Table 5.2 present the hotspot density (km^{-2}) for each land cover type focusing on areas that have not changed land cover type during 2011-2019. Fire frequency is greatest in shrub, matching results shown in Figure 4.6 for the 2011 to 2016 time period.

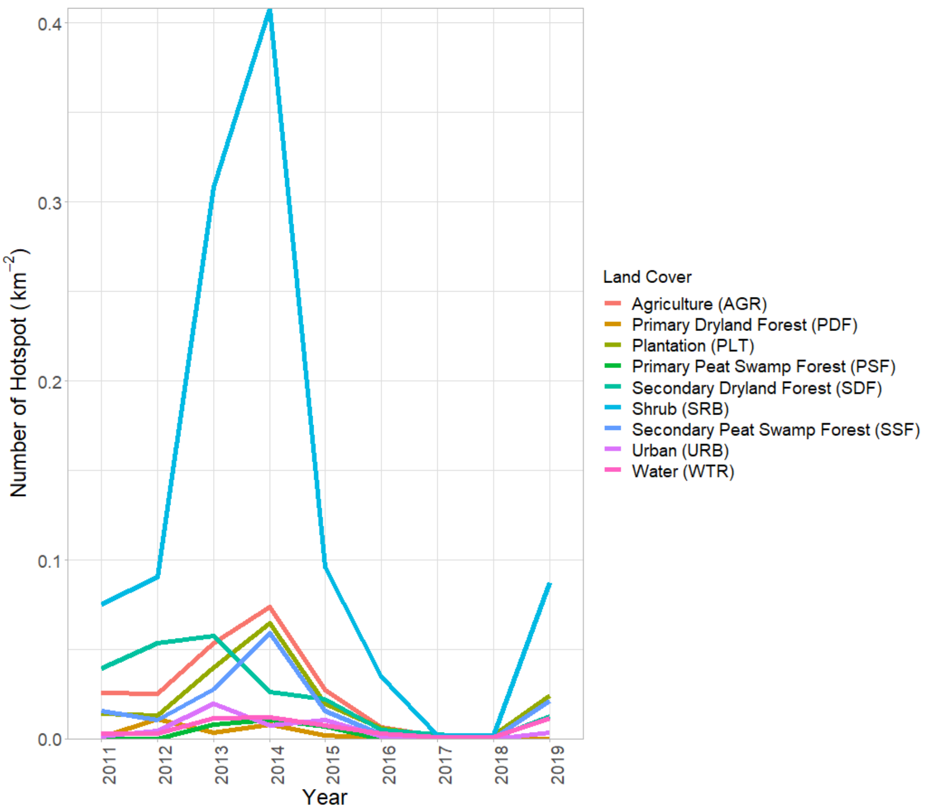


Figure 5.6 Hotspot density (km^{-2}) for each land cover type in unmodified areas (i.e., have not changed land cover type over the period considered) during 2011-2019.

Table 5.2 Hotspot density (km^{-2}) for each land cover type in unmodified areas during 2011-2019.

Land cover	2011	2012	2013	2014	2015	2016	2017	2018	2019
AGR	0.026	0.025	0.054	0.074	0.027	0.007	0.001	0.001	0.021
PDF	0.001	0.011	0.004	0.008	0.002	0.001	0	0	0
PLT	0.014	0.013	0.04	0.065	0.02	0.006	0.001	0.002	0.024
PSF	0	0	0.008	0.011	0.007	0	0	0	0.004
SDF	0.039	0.054	0.057	0.026	0.022	0.005	0.002	0	0.013
SRB	0.075	0.09	0.308	0.408	0.096	0.035	0.002	0.002	0.088
SSF	0.015	0.01	0.028	0.059	0.016	0.002	0	0.001	0.021
URB	0.001	0.005	0.02	0.008	0.011	0.002	0	0	0.004
WTR	0.003	0.003	0.011	0.012	0.007	0.003	0.001	0.001	0.012

The land cover change diagram in Figure 5.7 and detailed in Table 5.3, shows conversion of shrub (SRB) to plantation (PLT) and agriculture (AGR). Compared to the transition in Figure 4.3 that began in 2006, in 2011 it was seen that plantation (PLT) had increased from 31 to 34%, shrub (SRB) rose 5% to 25% while secondary peat swamp forest (SSF) dropped to 15% from 21%. The expansion of plantation (PLT) continued reaching 45% in 2017 while secondary peat swamp forest (SSF) kept shinking to 13%. On the other hand, shrubs that increased in 2011 reduced to less than the occurrence in 2006 to 15% due toconvsion into plantation and (PLT) and agriculture (AGR).

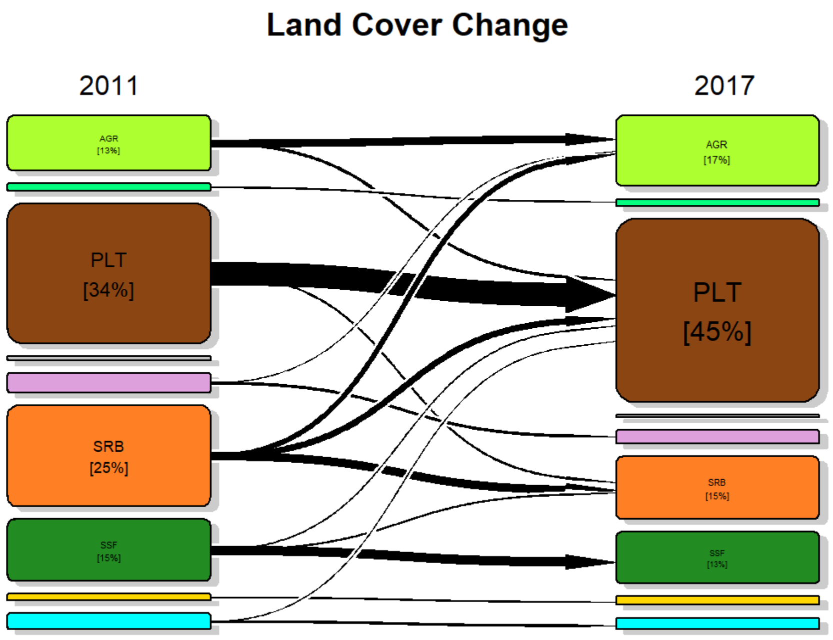


Figure 5.7 Land cover change (2011-2019).

Table 5.3 Land cover change matrix (2011-2019).

Land cover 2019										
Land cover 2011	"AGR"	"PDF"	"PLT"	"PSF"	"SDF"	"SRB"	"SSF"	"URB"	"WTR"	Subtotal 2011 LC
"AGR"	8923	0	2975	0	1	39	12	316	12	12278
"PDF"	18	1497	3	0	90	8	0	0	0	1616
"PLT"	213	0	28646	0	64	1917	181	66	1	31088
"PSF"	3	0	14	553	0	27	322	0	0	919
"SDF"	586	5	331	9	2848	460	76	9	4	4328
"SRB"	5651	0	7005	0	8	9604	121	91	69	22549
"SSF"	302	0	1081	0	5	1605	10739	0	10	13742
"URB"	1	0	40	0	0	3	2	1447	0	1493
"WTR"	27	0	757	0	0	252	9	6	2490	3541
Subtotal 2019 LC	15724	1502	40852	562	3016	13915	11462	1935	2586	91554

The cumulative percentage of number of year with fire by land cover transitions is exposed in Figure 5.8 and Table 5.4. Note that only major transitions involving more than 200 cells are shown. Annual land cover type is available only between 2011-2017, with 2018 and 2019 land cover assumed to be identical to 2017. Fire occurrences are derived from 2011-2019 hotspot dataset. When the value of nYear_Fire in the x-axis of the graph (or the column “Number of year with fire occurrences” of the table) is zero this refers to percentage of cells in each land cover transition where there is no single year with fire between 2011 and 2019. Regions that did not change land-cover type are most likely to have no incidences of fire. For example, unchanged agriculture (AGR-AGR), secondary dryland forest (SDF-SDF), plantation (PLT-PLT), and secondary peat swamp forest (SSF-SSF) accounted for very high proportion of non fire cells (more than 90%). On the other hand, regions that changed land-cover type, such as secondary dryland forest converted to plantation (SDF-PLT), shrub (SDF-SRB) and agriculture (SDF-AGR) and secondary peat swamp forest to shrub (SSF-SRB) have less than 50% non-fire cells. From nine years of observation, around 90% of cells in each land cover transition have non-fire years, or 1-2 years with fire. For example, the shrub to plantation (SRB-PLT) which has the largest number of cells with fire (2076) consist of 70% non-fire cells, 18% cells with a single year with fire and 8% cells with two year (don’t have to be consecutive) experienced fire.

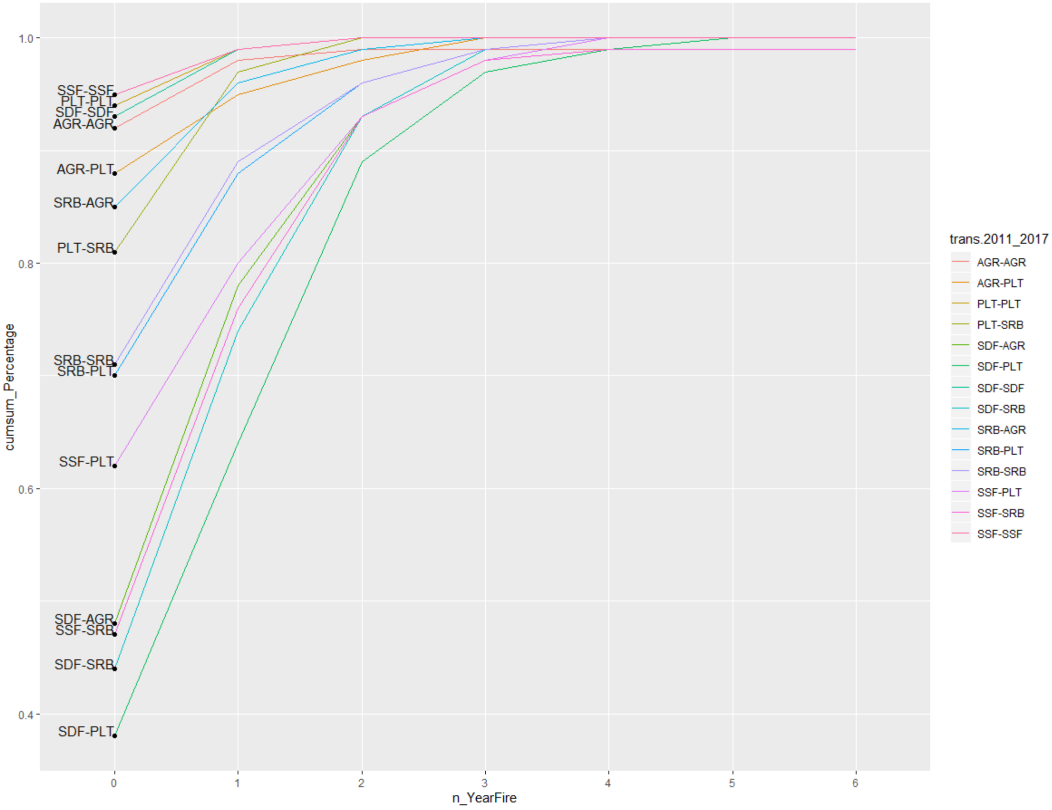


Figure 5.8 Cumulative percentage of number of year with fire by land cover transitions.

Table 5.4 Fraction of number of year with fire w.r.t total cell in land cover transition.

	Number of year with fire occurrences									
Transition 2011-2017	0	1	2	3	4	5	6	Cell in transition	Cell with fire	Fraction cell with fire
"SDF-PLT"	0.38	0.26	0.25	0.08	0.02	0.01	0	331	206	0.622
"SDF-SRB"	0.44	0.3	0.19	0.06	0.01	0	0	460	259	0.563
"SSF-SRB"	0.47	0.29	0.17	0.05	0.01	0	0	1605	851	0.530
"SDF-AGR"	0.48	0.3	0.15	0.05	0.01	0	0	586	303	0.517
"SSF-PLT"	0.62	0.18	0.13	0.05	0.02	0	0	1081	411	0.380
"SRB-PLT"	0.7	0.18	0.08	0.03	0.01	0	0	7005	2076	0.296
"SRB-SRB"	0.71	0.18	0.07	0.03	0.01	0	0	9604	2754	0.286
"PLT-SRB"	0.81	0.16	0.03	0	0	0	0	1917	371	0.193
"SRB-AGR"	0.85	0.11	0.03	0.01	0	0	0	5651	857	0.151
"AGR-PLT"	0.88	0.07	0.03	0.02	0	0	0	2975	352	0.118
"AGR-AGR"	0.92	0.06	0.01	0	0	0	0	8923	700	0.078
"SDF-SDF"	0.93	0.06	0.01	0	0	0	0	2848	209	0.073
"PLT-PLT"	0.94	0.05	0.01	0	0	0	0	28646	1771	0.061
"SSF-SSF"	0.95	0.04	0.01	0	0	0	0	10740	539	0.050

Figure 5.9 shows annual hotspot densities are higher in peat land than non-peat areas. Fires occur in regions with a wide range of initial tree cover. Higher hotspot densities are found in regions with medium tree cover in 2000 which lost much of their tree cover between 2011-2019. In peat land areas, low fire intensity is found in undisturbed region (0-10% tree cover loss) and already deforested regions (had very small fraction of tree cover in 2000). These results are similar compared to the situation experienced between 2000 and 2012 (Figure 3.3), with peatland areas more vulnerable than non-peatland but fire was more intensive in the 2011-2019 period.

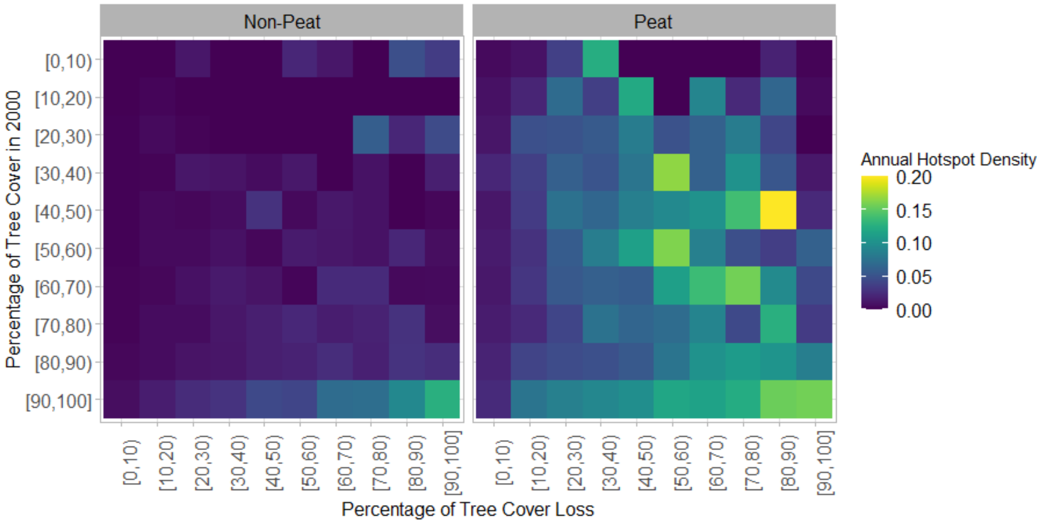


Figure 5.9 Annual hotspot density (km^{-2}yr^{-1}) between 2011 and 2019 as a function of percentage of tree cover loss (2011 to 2017) and percentage tree cover in the year 2000 for non-peat and peat regions.

5.3.1 Result of hotspot count prediction using tree cover loss and land system (HotspotCount_LossPeat-LM)

Figure 5.10 shows the marginal density of hotspot count and loss percentage by land system, where most area studied has no hotspot while large areas experienced low-medium loss especially in non peat land.

```
Residuals:
    Min      1Q  Median      3Q     Max 
-56.254  -5.823  -1.858   0.991 190.177 

Coefficients:
                        Estimate Std. Error t value Pr(>|t|)    
(Intercept)              -0.9913     0.5093  -1.946   0.0517 .  
Loss_pct                 31.6585     2.5169  12.578  < 2e-16 ***
LandsystemPeat            4.5545     0.8157   5.583 2.52e-08 ***
Loss_pct:LandsystemPeat  28.2175     3.5219   8.012 1.48e-15 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 17.92 on 3914 degrees of freedom
Multiple R-squared:  0.2241, Adjusted R-squared:  0.2235 
F-statistic: 376.7 on 3 and 3914 DF,  p-value: < 2.2e-16
```

Figure 5.11 shows that hotspot count has a linear relationship with percentage of tree cover loss, and the ratio of change is double in peat land. Even though loss percentage and land system are significant variables in the equations, they explain around 20% of hotspot count variability in non peat areas and 15% of it in peat areas. Furthermore, the local regressions with “loess” show a more intense hotspot count in non peat where the loss is greater than 50% and less in peat area with a high loss degree. Further detail is available at Box 1.

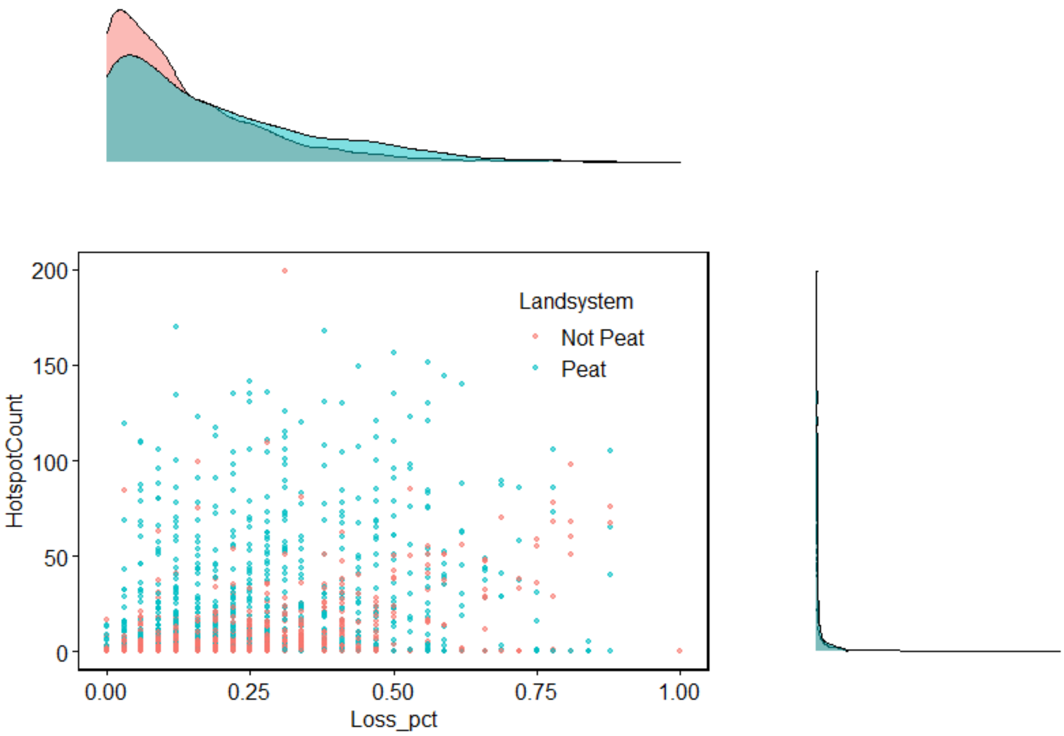


Figure 5.10 Marginal Density Plot of HotspotCount and Loss Percentage by Land System.

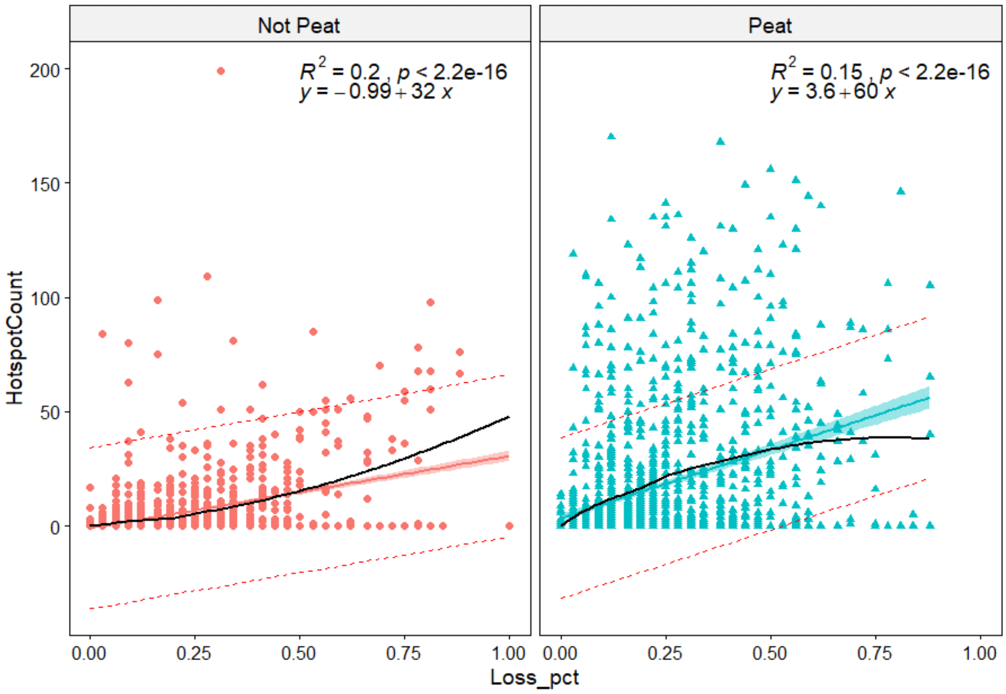


Figure 5.11 Loss Percentage - Landsystem interaction to predict Hotspot. Colored lines show linear regression for non-peat and peat regions, black lines show its corresponding loess local regression, the confidence bands as shadows and the prediction band of 95% confidence level as red dash lines.

Box 1 Summary of HotspotCount_LossPeat-LM

```
Residuals:
    Min      1Q  Median      3Q     Max 
-56.254  -5.823  -1.858   0.991 190.177 

Coefficients:
                        Estimate Std. Error t value Pr(>|t|)    
(Intercept)              -0.9913     0.5093  -1.946   0.0517 .  
Loss_pct                 31.6585     2.5169  12.578  < 2e-16 ***
LandsystemPeat            4.5545     0.8157   5.583 2.52e-08 ***
Loss_pct:LandsystemPeat  28.2175     3.5219   8.012 1.48e-15 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 17.92 on 3914 degrees of freedom
Multiple R-squared:  0.2241, Adjusted R-squared:  0.2235 
F-statistic: 376.7 on 3 and 3914 DF,  p-value: < 2.2e-16
```

Therefore the prediction formulas are :

For Non Peat: HotspotCount = -0.9913 +31.6585 Loss_pct

For Peat: HotspotCount = (-0.9913 + 4.5545) + (31.6585 +28.2175) Loss_pct

= 3.5632+ 59.876 Loss_pct

5.3.2 Result of hotspot mean prediction using tree cover loss and land system (HotspotMean_LossPeat-LM)

Here, linear models are built to predict average hotspot occurrences in that period based on percentage of tree cover loss and land system (Peat/Non-Peat). Both additive (Figure 5.12, Box 2) and with-interaction (Figure 5.13, Box 3) models show that tree cover loss lead to a more severe hotspot especially in peat-land areas. It is noticeable that in GLM with-interaction, the loss percentage coefficient for peat-land is almost double that from non-peat.

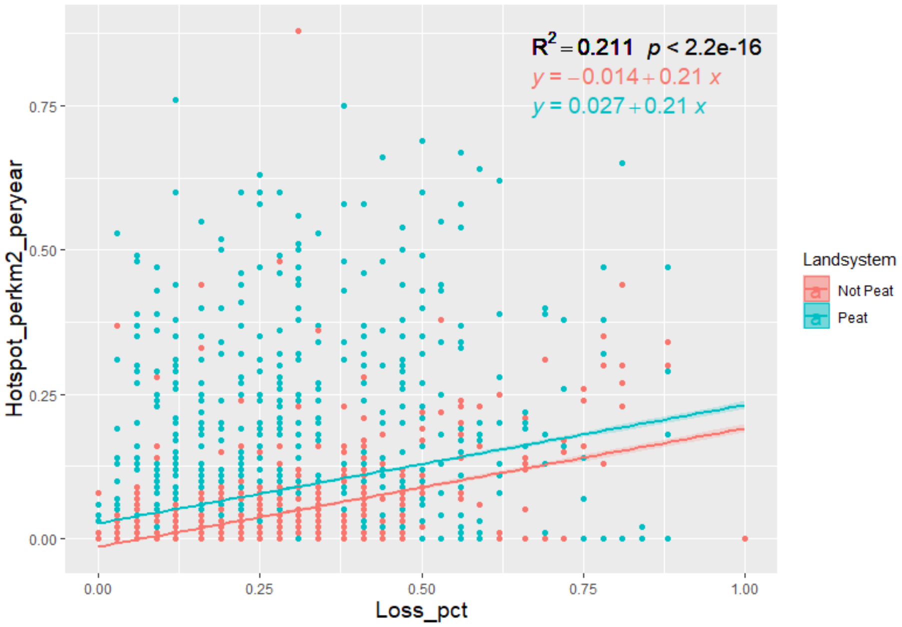


Figure 5.12 Additive Linear Model.

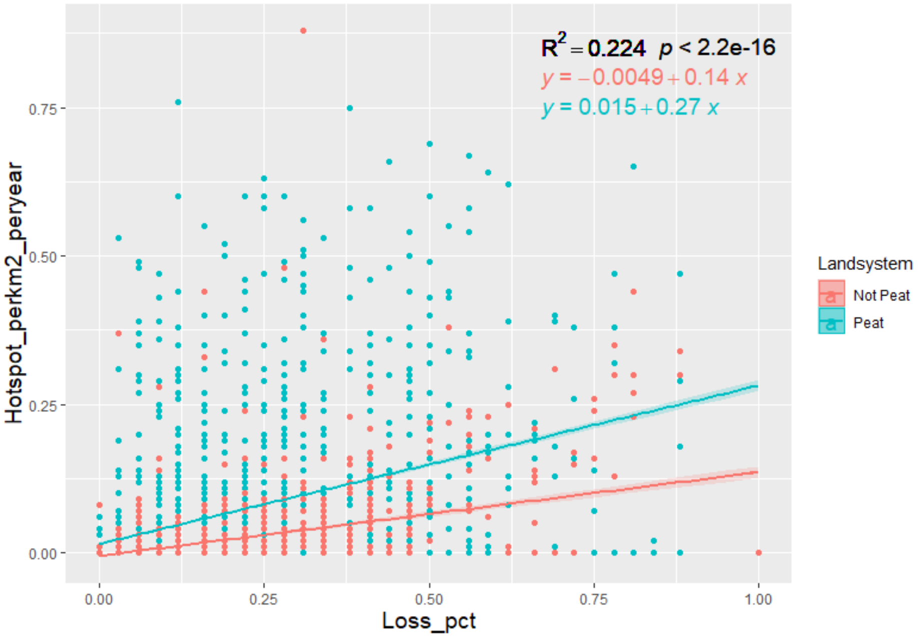


Figure 5.13 Linear Model With-Interaction.

Box 2 Summary of the additive linear model.

```
Residuals:
     Min       1Q   Median       3Q      Max 
-0.20728 -0.03299 -0.00529  0.01366  0.83010 

Coefficients:
                Estimate Std. Error t value Pr(>|t|)    
(Intercept)    -0.013661   0.002002  -6.825 1.02e-11 ***
Loss_pct        0.205047   0.007907  25.933  < 2e-16 ***
LandsystemPeat  0.040500   0.002636  15.363  < 2e-16 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1 

Residual standard error: 0.08048 on 3915 degrees of freedom
Multiple R-squared:  0.2111, Adjusted R-squared:  0.2107 
F-statistic: 523.7 on 2 and 3915 DF,  p-value: < 2.2e-16
```

Therefore the equation are :

For Non Peat: HotspotCount = -0.013661+ 0.205047Loss_pct

For Peat: HotspotCount = (-0.013661+ 0.040500) + 0.205047Loss_pct

= 0.026839+ 0.205047Loss_pct

Box 3 Summary of the linear model with-interaction

```
Residuals:
     Min       1Q   Median       3Q      Max 
-0.25003 -0.02610 -0.00781  0.00486  0.84121 

Coefficients:
                         Estimate Std. Error t value Pr(>|t|)    
(Intercept)             -0.004856   0.002269  -2.140   0.0324 *  
Loss_pct                 0.140778   0.011214  12.554  < 2e-16 ***
LandsystemPeat           0.020261   0.003634   5.575 2.64e-08 ***
Loss_pct:LandsystemPeat  0.125836   0.015691   8.020 1.39e-15 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1 

Residual standard error: 0.07983 on 3914 degrees of freedom
Multiple R-squared:  0.2238, Adjusted R-squared:  0.2232 
F-statistic: 376.2 on 3 and 3914 DF,  p-value: < 2.2e-16
```

For Non Peat: Hotspot_perkm2_peryear = -0.004856 +0.140778 Loss_pct

For Peat: Hotspot_perkm2_peryear = (-0.004856 + 0.020261) +
(0.140778+0.125836) Loss_pct

= 0.015405+ 0.266614 Loss_pct

5.3.3 Result of hotspot count prediction using land cover transition (HotspotCount_Landcover_Transition-GLM)

In this scheme, land cover transition is observed inside 5 km x 5 km areas and derived from original 1 km^2 cells. Land transformation can be focused on the beginning of transition (Figure 5.2), for example 2975 km^2 out of 12278 km^2 (24%) of agriculture (AGR) in 2011 had changed into plantation (PLT) in 2019. Similarly, from 22549 km^2 of shrub (SRB) in 2011, 7005 km^2 (31%) transformed into plantation (PLT) and 5651 km^2 (25%) to agriculture (AGR). Analysis of land cover change can pay more attention on the condition at the end of transition (Figure 5.3), for instance plantation (PLT) in 2019 covers 40852 km^2 of which 17% was previously shrub (SRB), 7% was agriculture (AGR) and 2% was secondary peat swamp forest (SSF). In this aggregate unit, land cover dynamics during 2011-2019 are reflected by the number of stable land cover type and number of cells which had been transformed. Therefore, the modification measured as number of cells in 2011 which had changed by 2019 (Table 5.5) and and number of cells in 2019 which come from another land cover change in 2011 (Table 5.6).

Table 5.7 displays hotspot occurrences related to land cover change in the 2011-2019 period. To simplify land use transformation then classes that rarely changed and with low fire density land cover such as water (WTR) and urban (URB) are excluded from the analysis. The hotspot occurrences is relatively well predicted by the end of transition oriented model (Table 5.8) where the R^2 values refer to the results of rsq.v variance-function-based library (Zhang, 2017; Zhang, 2020) and p values calculated using rcompanion library (Mangiafico, 2020). In addition, primary dryland forest (PDF) and primary peat swamp forest (PSF) are significant in the beginning of land cover transitions, while secondary dryland forest (SDF) is significant at the end of transition (Table 5.9).

Table 5.5 Stable and Changed 2011 Land Cover.

Land type	Land Stable Area	Land Changed Area	Land Stable % w.r.t 2011	Land Changed % w.r.t 2011
"AGR"	8923	3355	0.73	0.27
"PDF"	1497	119	0.93	0.07
"PLT"	28646	2442	0.92	0.08
"PSF"	553	366	0.60	0.40
"SDF"	2448	1480	0.56	0.44
"SRB"	9604	12945	0.43	0.57
"SSF"	10739	3003	0.78	0.22

Table 5.6 The 2019 original and result from other land cover.

Land type	Land Stable Area	To be Land Area	Land Stable % w.r.t 2019	To be Land % w.r.t 2019
"AGR"	8923	6801	0.57	0.43
"PDF"	1497	5	0.99	0.01
"PLT"	28646	12206	0.70	0.30
"PSF"	553	9	0.98	0.02
"SDF"	2448	168	0.82	0.18
"SRB"	9604	4311	0.69	0.31
"SSF"	10739	723	0.94	0.06

Table 5.7 Hotspot Occurrences w.r.t Land Cover Change Matrix 2011-2019.

Land Cover 2019

		AGR	PDF	PLT	PSF	SDF	SRB	SSF	Subtotal 2011 LC
Land Cove 2011	AGR	1238	0	1012	0	0	16	1	2267
	PDF	7	16	0	0	25	4	0	52
	PLT	133	0	3969	0	13	1188	40	5343
	PSF	11	0	19	9	0	26	14	79
	SDF	630	0	598	0	284	587	4	2103
	SRB	1791	0	5861	0	0	8179	41	15872
	SSF	368	0	1543	0	0	2914	1043	5868
	Subtotal 2019 LC	4178	16	13002	9	322	12914	1143	31584

Table 5.8 HotspotCount_Landcover_Transition-GLM model results.

Model	RMSE	SER	R^2	*P*
Begin of transition oriented	21.86209	46.81348	0.2589969	< 2.2e-16
End of transition oriented	21.88628	46.81348	0.2789561	< 2.2e-16

Table 5.9 HotspotCount_Landcover_Transition-GLM model coefficients.

	Begin of transition oriented		End of transition oriented	
Variable	Estimate	Signif.code	Estimate	Signif.code
(Intercept)	-0.455907	***	-0.602842	***
AGR_stable	0.051748	***	0.058371	***
PDF_stable	-0.020989	*	-0.017226	.
PLT_stable	0.053427	***	0.055536	***
PSF_stable	0.059209	***	0.049394	***
SDF_stable	-0.005875		0.040385	***
SRB_stable	0.177065	***	0.182005	***
SSF_stable	0.041370	***	0.053995	***
AGR_&	0.109859	***	0.114154	***
PDF_&	0.148586	***	-0.224781	
PLT_&	0.162680	***	0.155993	***
PSF_&	0.067935	***	-8.744994	

SDF_&	0.192362	***	0.088481	***
SRB_&	0.131306	***	0.218708	***
SSF_&	0.211374	***	0.037391	***

Signif. codes: 0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

& refers to “changed” in begin transition oriented and to “to be” in end transition oriented

5.3.4 Result of hotspot count prediction based on landcover dynamics (HotspotCount_Landcover_Transition_LossPeat-GLM)

The GLM model with Poisson link is used to predict Hotspot Count based on landcover dynamics in 25 km^2 areas as well as tree cover loss and land system. This scheme gives RMSE of 20.83656. Here, numbers of each land cover change pair in 1 km^2 cells (for an example is Table 5.10) are weighted by hotspot density i.e. number of hotspot per kilometre square of land transition area (

Table 5.11). Here, the HotspotDensity weighted variable is the smallest positive estimator (Box 4).

Table 5.12 shows the result of this procedure for the sample case. Furthermore, the score for a certain land cover in 2011 changing to any land cover in 2019 are summed up and gives the potential risk of each land cover type modification (Table 5.12 Example of weighted land cover transition, potential risk column). The risk values are then multiplied by the percentage of hotspot 2011-2019 for each land cover type in 2019 (Table 5.12, Copied from row subtotal 2019 LC in Table 5.7), then summarized to find total score (574.8834 for our sample cell). Figure 5.14 shows that all hotspot.bin spread at all hotspot density values.

Table 5.10 Example of land cover transition matrix of a 5 km x 5 km cell.

Land cover 2011	Land cover 2019						
	AGR	PDF	PLT	PSF	SDF	SRB	SSF
AGR	0	0	8	0	0	0	0
PDF	0	0	0	0	0	0	0
PLT	0	0	0	0	0	0	0
PSF	0	0	0	0	0	0	0
SDF	0	0	0	0	0	0	0
SRB	2	0	15	0	0	0	0
SSF	0	0	0	0	0	0	0

Table 5.11 Hotspot density of land cover transition.

		Land cover 2019						
		AGR	PDF	PLT	PSF	SDF	SRB	SSF
Land cover 2011	AGR	0.138	0.000	0.340	0.000	0.000	0.410	0.083
	PDF	0.389	0.010	0.000	0.000	0.278	0.500	0.000
	PLT	0.624	0.000	0.138	0.000	0.203	0.619	0.221
	PSF	3.667	0.000	1.357	0.016	0.000	0.963	0.043
	SDF	1.075	0.000	1.806	0.000	0.099	1.276	0.052
	SRB	0.317	0.000	0.836	0.000	0.000	0.851	0.338
	SSF	1.218	0.000	1.427	0.000	0.000	1.815	0.097

Table 5.12 Example of weighted land cover transition.

Land cover 2011	Land cover 2019							potential risk (a)	Percentage of hotspot 2011-2019 (b)	(a) x (b)
	AGR	PDF	PLT	PSF	SDF	SRB	SSF			
AGR	0	0	2.721	0	0	0	0	2.721	13.228	35.99339
PDF	0	0	0	0	0	0	0	0	0.0506	0
PLT	0	0	0	0	0	0	0	0	41.166	0
PSF	0	0	0	0	0	0	0	0	0.0285	0
SDF	0	0	0	0	0	0	0	0	1.0195	0
SRB	0.63	0	12.550	0	0	0	0	13.18	40.887	538.8907
SSF	0	0	0	0	0	0	0	0	3.6189	0
									Total score	574.8834

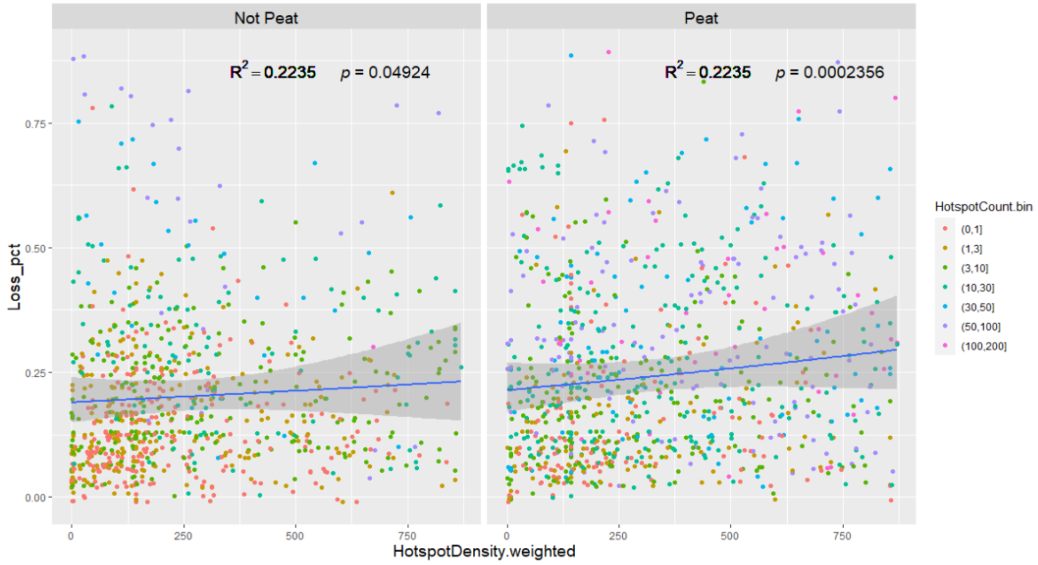
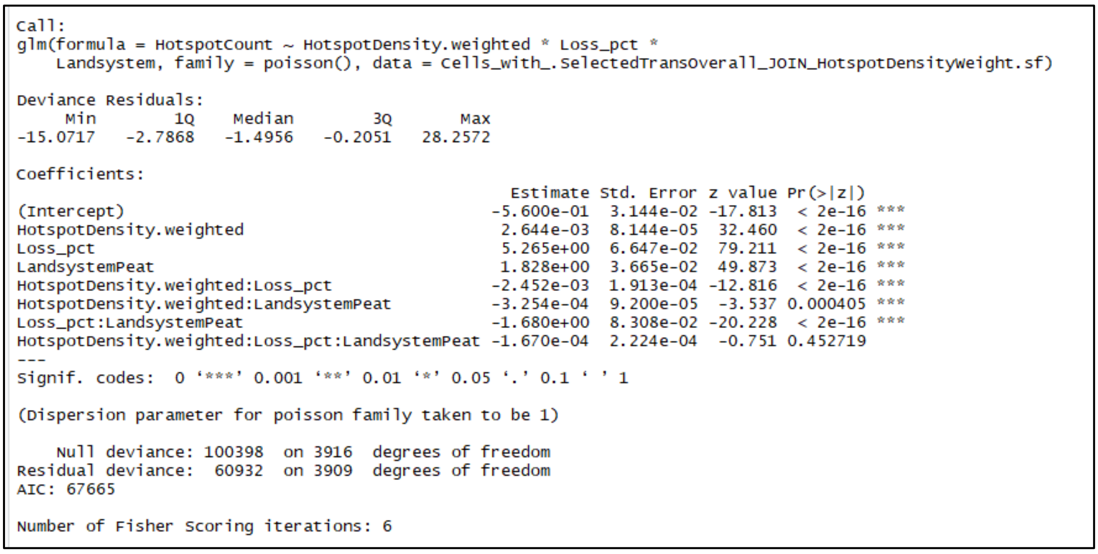


Figure 5.14 Hotspot count by weighted land cover transition, tree cover loss and land system.

Box 4 Summary of hotspot count by weighted land cover transition, tree cover loss and land system GLM.



```
Call:
glm(formula = HotspotCount ~ HotspotDensity.weighted * Loss_pct *
    Landsystem, family = poisson(), data = Cells_with_.SelectedTransOverall_JOIN_HotspotDensityWeight.sf)

Deviance Residuals:
     Min        1Q    Median        3Q       Max
-15.0717   -2.7868   -1.4956   -0.2051   28.2572

Coefficients:
                                              Estimate Std. Error z value Pr(>|z|)
(Intercept)                                 -5.600e-01  3.144e-02 -17.813  < 2e-16 ***
HotspotDensity.weighted                      2.644e-03  8.144e-05  32.460  < 2e-16 ***
Loss_pct                                     5.265e+00  6.647e-02  79.211  < 2e-16 ***
LandsystemPeat                               1.828e+00  3.665e-02  49.873  < 2e-16 ***
HotspotDensity.weighted:Loss_pct            -2.452e-03  1.913e-04 -12.816  < 2e-16 ***
HotspotDensity.weighted:LandsystemPeat      -3.254e-04  9.200e-05  -3.537 0.000405 ***
Loss_pct:LandsystemPeat                     -1.680e+00  8.308e-02 -20.228  < 2e-16 ***
HotspotDensity.weighted:Loss_pct:LandsystemPeat -1.670e-04  2.224e-04  -0.751 0.452719
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for poisson family taken to be 1)

    Null deviance: 100398  on 3916  degrees of freedom
Residual deviance:  60932  on 3909  degrees of freedom
AIC: 67665

Number of Fisher Scoring iterations: 6
```

5.3.5 Result of Geographically Weighted Regression

Previously we realized that hotspot events not evenly distributed (Figure 5.4). Evaluating hotspot count in 5 km x 5 km area (as y variable) with their 8 neighbourhood (as ww variable) gives Moran’s I value of 0.5046935 which emphasize the fact the fire hotspots are clustered (Box 5). Furthermore, Figure 5.15 shows a plot of hotspot count in certain cells versus their spatially lag. Spatial lag is the sum of spatially-weighted values of neighbouring cells. The relationship has a slope of 0.47210 and adjusted R-squared of 0.3826, suggesting aspatial relationship. Figure 5.16 displays regions with values that highly differ to their neighbours such as in Dumai and near border with South Sumatra Province.

Box 5 Moran test

```
moran.test(y, ww, randomisation=FALSE)
                    Moran I test under normality
data:  y
weights: ww

Moran I statistic standard deviate = 63.04, p-value < 2.2e-16
alternative hypothesis: greater
sample estimates:
Moran I statistic       Expectation        Variance
    5.046935e-01     -2.488800e-04      6.415705e-05
```

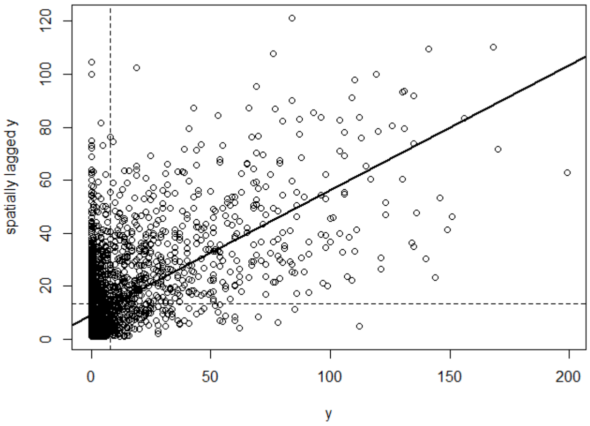


Figure 5.15 Spatial lag of hotspot count (y).
Dashed lines indicate means value and solid line is regression line.

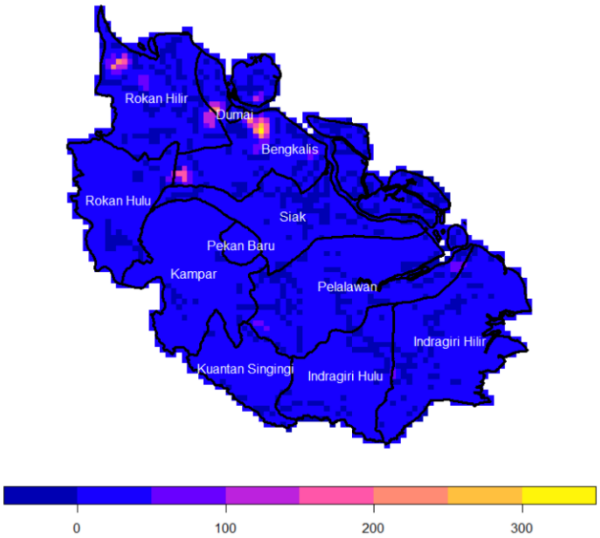


Figure 5.16 Local Moran of Hotspot Count.

Using the lm(HotspotCount~Loss_pct * Landsystem) formula to predict hotspot count based on percentage of tree cover loss and land system (peat/non-peat) gives an adjusted R-squared of 0.2235(Box 6)..

```
Residuals:
    Min      1Q  Median      3Q     Max 
-56.254  -5.823  -1.858   0.991 190.177 

Coefficients:
                        Estimate Std. Error t value Pr(>|t|)    
(Intercept)              -0.9913     0.5093  -1.946   0.0517 .  
Loss_pct                 31.6585     2.5169  12.578  < 2e-16 ***
LandsystemPeat            4.5545     0.8157   5.583 2.52e-08 ***
Loss_pct:LandsystemPeat  28.2175     3.5219   8.012 1.48e-15 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 17.92 on 3914 degrees of freedom
Multiple R-squared:  0.2241, Adjusted R-squared:  0.2235 
F-statistic: 376.7 on 3 and 3914 DF,  p-value: < 2.2e-16
```

Their residual map is also shown (Figure 5.17)

Box 6 Summary of linear model of hotspot count based on percentage of tree cover loss and land system.

```
Residuals:
    Min      1Q  Median      3Q     Max 
-56.254  -5.823  -1.858   0.991 190.177 

Coefficients:
                        Estimate Std. Error t value Pr(>|t|)    
(Intercept)              -0.9913     0.5093  -1.946   0.0517 .  
Loss_pct                 31.6585     2.5169  12.578  < 2e-16 ***
LandsystemPeat            4.5545     0.8157   5.583 2.52e-08 ***
Loss_pct:LandsystemPeat  28.2175     3.5219   8.012 1.48e-15 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 17.92 on 3914 degrees of freedom
Multiple R-squared:  0.2241, Adjusted R-squared:  0.2235 
F-statistic: 376.7 on 3 and 3914 DF,  p-value: < 2.2e-16
```

The distribution of local R^2 (

Figure 5.18) are high in Rokan Hilir, Dumai, Pelalawan and Pulau Meranti districts. Furthermore, the land system gives a strong influence on the number of hotspots in Rokan Hilir district - South Sumatra province boundary (Figure 5.19) and in Dumai district. On the other hand, loss count are crucial in Dumai district and area between Pelalawan district and Siak district (Figure 5.20) coefficients. Figure 5.21 shows actual versus predicted hotspot count, which has RMSE of 11.16622.

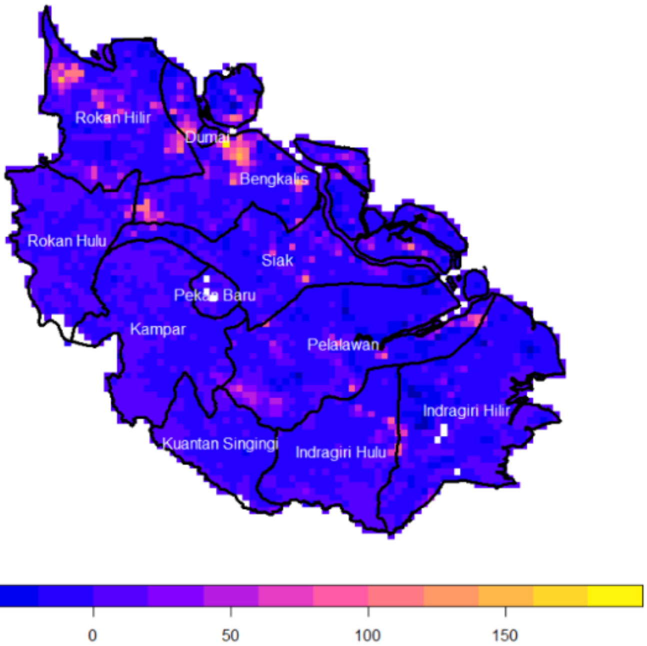


Figure 5.17 Residual map of hotspot count prediction.

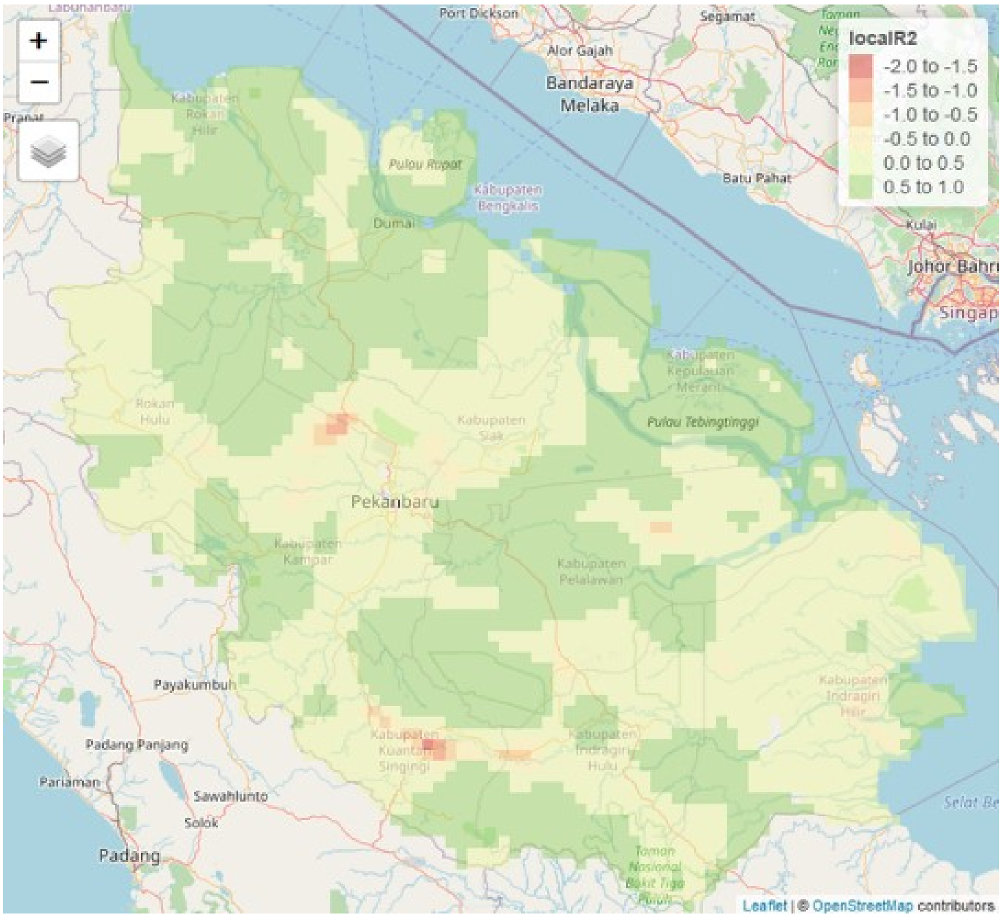


Figure 5.18 GWR local R^2 – with interaction.

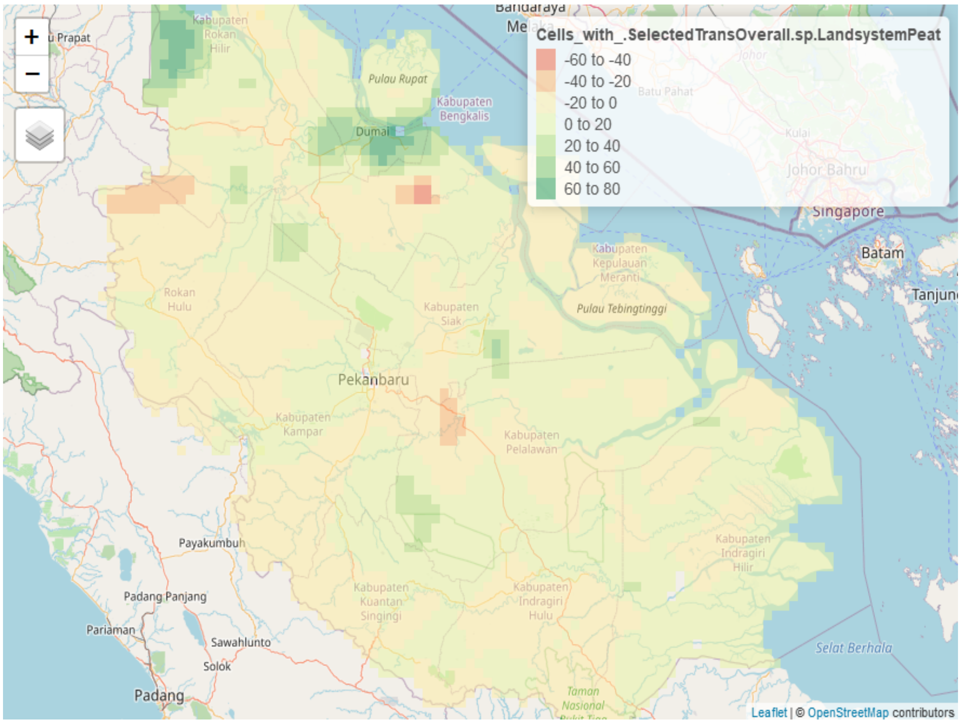


Figure 5.19 GWR land system – with interaction.

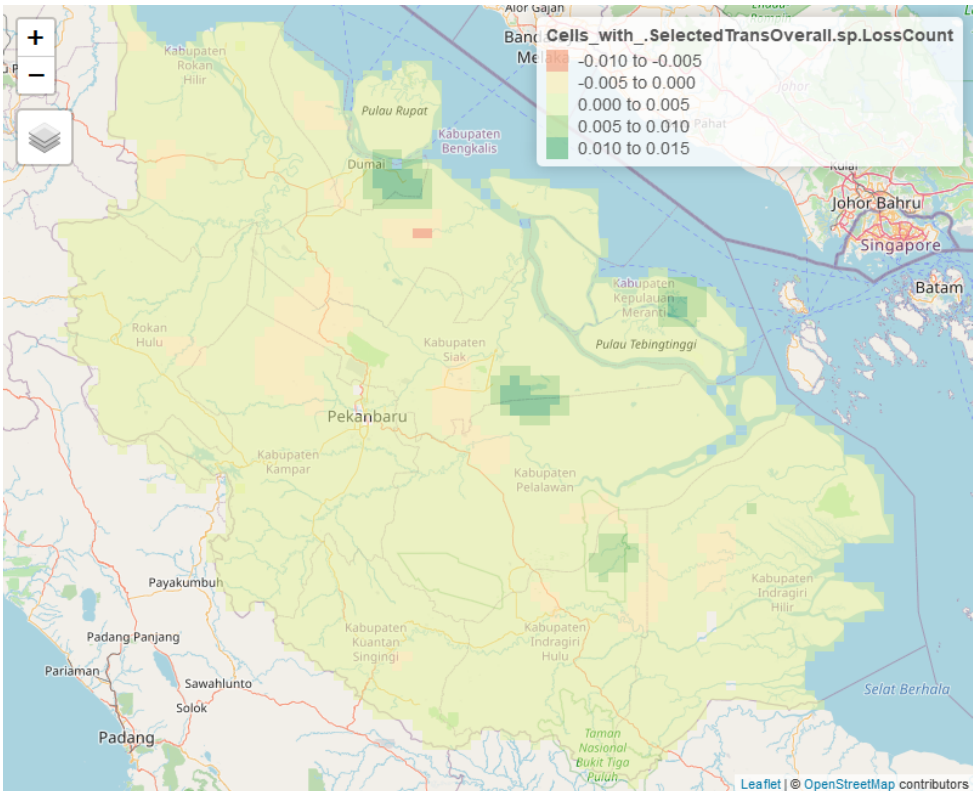


Figure 5.20 GWR loss count – with interaction.

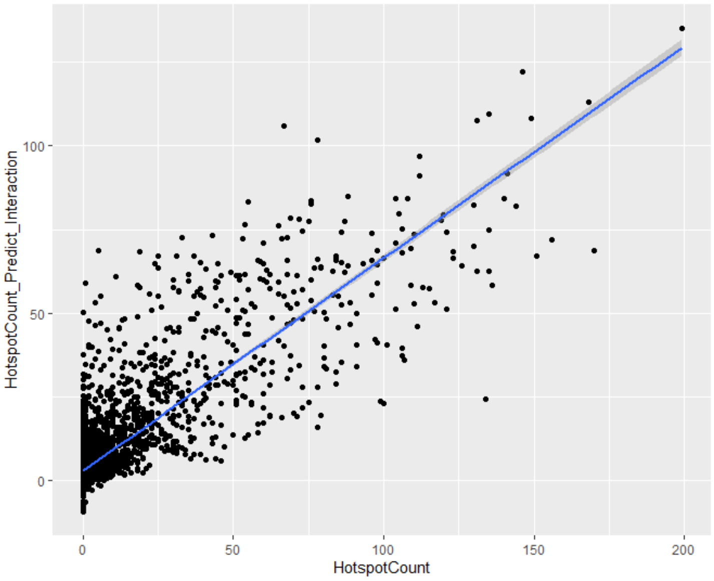


Figure 5.21 Actual vs Predicted Hotspot Count (GWR with interaction).

5.4 Discussion

Table 5.13 summarizes results from the different schemes.

Table 5.13 Schemes result

Scheme	R^2
HotspotCount_LossPeat-LM	0.2 (non-peat) and 0.15 (peat)
HotspotMean_LossPeat-LM (without interaction)	0.211
HotspotMean_LossPeat-LM (with interaction)	0.224
HotspotCount_Landcover_Transition-GLM (Begin of transition oriented)	0.259
HotspotCount_Landcover_Transition-GLM (End of transition oriented)	0.279
HotspotCount_Landcover_Transition_LossPeat-GLM	0.224
Geographically Weighted Regression	0.224

Hotspot characteristics (count and mean) are modelled using tree cover loss and land system (peat/non-peat) in 25 km^2 cells (HotspotCount_LossPeat-LM and HotspotMean_LossPeat-LM). The number of hotspot inside 25 km^2 area in 2011-2019 ranges from 0 to 199. When hotspot count is estimated from tree cover loss and land system, we found a unit of tree cover loss percentage will increase the hotspot count around 32 occurences in non-peat area and almost 69 occurences in peat. Similarly, in HotspotMean_LossPeat-LM with-interaction, the loss percentage coefficient for peat-land is almost double from that in non-peat.

So far, hotspot tendencies are predicted based on land cover label for each year only. Moreover, in HotspotCount_Landcover_Transition-GLM land cover transition inside 5 km x 5km areas during 2011-2019 are reflected by the number of stable land cover type and the number of cells which had been transformed. Both “beginning of transition oriented” and “end of transition oriented” models produce the same RMSE (21.8). This value is ten times that for the model with landcover predictor (HotspotCount_Landcover-GLM), probably due to transition generalization as “changed” or “to be” will obscure specific transitions which have higher link to fire. For instance, there were more fire in shrub (SRB) to plantation (PLT) transitions than agriculture (AGR) to plantation (PLT).

So, in HotspotCount_Landcover_Transition_LossPeat-GLM the land cover transitions are weighted by hotspot density and as a result gives better RMSE than HotspotCount_Landcover_Transition-GLM, although HotspotDensity weighted variable has the smallest positive estimator. Finally, the effect of spatial relationship is examined using Geographically Weighted Regression. Fire hotspots are spatially clustered as indicated by Moran’s I value 0.5046935. Predicting hotspot count based on percentage of tree cover loss and land system with regard to neighbourhood characteristic highlight some region and gives a RMSE of 11.16622.

The HotspotCount_LossPeat-LM scheme shows that forest loss on peatlands increases the chances of hotspots occurrences more than it does in non-peat land, which is in line with previous work (Sitanggang et al., 2013; Sumarga, 2017). However, the coefficient of determination in peatlands is lower than in non-peatland, which is possibly due to several important factors that have not been accounted for such as the type of peat (Sitanggang et al., 2013) or accessability based on low-elevation and steepness of slope (Sumarga, 2017).

The HotspotMean_LossPeat-LM scheme has higher R^2 than HotspotCount_LossPeat-LM, suggesting that the number of events (km^{-2} $year^{-1}$) may characterize fire hotspot better than hotspot count. Even though the HotspotMean_LossPeat-LM scheme shows the multiplicative effect of tree cover loss percentage, it has failed to consider that the occurrence of fires depends on time interval from land cover change (Adrianto et al., 2019; Siegert et al., 2001).

HotspotCount_Landcover_Transition-GLM provides slightly better R^2 than the previous schemes notably in the “end of transition oriented” model where secondary dryland forest is significant. The landcover transition included corresponds to the fact that different land cover show different fire weather characteristics (Nikonovas et al., 2019) and that the majority of fire is associated with transition of secondary forest (Adrianto et al., 2020).

In HotspotCount_Landcover_Transition_LossPeat-GLM scheme, the HotspotDensity.weighted variable is the smallest positive estimator and the scheme R^2 is not better than HotspotCount_Landcover_Transition-GLM. Therefore, different formula need to be applied to quantify land cover transition weight such as net change (Elz et al., 2015), dynamic degree (Sun et al., 2016) or information entropy (Yang, 2012). Also, it is beneficial to include plantation concession development status such as establishment, change permit or closure and vegetation cover condition.

Unlike other research which encourage the usage of spatial relationship to model fire occurrences, we did not find any significant difference between Geographically Weighted Regression (GWR) model and previous linear models. It is probable that the low fitness of GWR is a consequence of coarse 5 km by 5 km analytical base unit which, when expanded to their 8 neighbourhood cells, cover 15 km x 15 km area for the regression. We believe that some additional datasets could improve the model, for example forest edge buffer, distance to river network, elevation and distance to road (Langner et al., 2007; Sitanggang and Ismail, 2011; Sloan et al., 2017; Sumarga, 2017).

So far our research has only attempted to model the occurrence of fires and where they occur. In our opinion, previously mentioned schemes could be expanded to predict when fire will happen by adding weather variables such as rainfall, precipitation and The Southern Oscillation Index (Cahyono et al., 2013; Field and Shen, 2008; Gaveau et al., 2014; Sloan et al., 2017; Stolle and Lambin, 2003).

5.5 Conclusion

In 25 km^2 cells we found that each additional one percent of tree cover loss increases the hotspot count up to 56 occurences with on average around 30 in non-peat area and almost 69 in peat land area. Similarly, the increment of hotspot mean due to tree cover loss in peat land is double than that in non-peatland areas. We also found that weighting the land cover transitions by the hotspot density improves the result. Finally, Moran’s I value show that fire hotspots are spatially clustered and we found Geographically Weighted Regression is useful to accommodate neighbourhood areas characteristics.

We found no model able to accurately predict hotspot severity based on the hotspot and land historical record with currently available datasets and spatio-temporal scale. However, models did give some useful indications of where fire frequency is higher. Whenever available, we suggest to include weather datasets, peat type and depth, river and road network, elevation and plantation development status and vegetation cover condition. In addition, we recommend focusing on the transition of secondary forest into plantation or shrub as these areas experience considerable fire.

Bibliography

Abood, S.A., Lee, J.S.H., Burivalova, Z., Garcia-Ulloa, J. and Koh, L.P. 2015. Relative Contributions of the Logging, Fiber, Oil Palm, and Mining Industries to Forest Loss in Indonesia. *Conservation Letters.* **8**(1), pp.58-67.10.1111/conl.12103

Adrianto, H.A., Spracklen, D.V. and Arnold, S.R. 2019. Relationship between Fire and Forest Cover Loss in Riau Province, Indonesia between 2001 and 2012. *Forests.* **10**(10).10.3390/f10100889

Adrianto, H.A., Spracklen, D.V., Arnold, S.R., Sitanggang, I.S. and Syaufina, L. 2020. Forest and Land Fires Are Mainly Associated with Deforestation in Riau Province, Indonesia. *Remote Sensing.* **12**(1).https://doi.org/10.3390/rs12010003

Alencar, A., Asner, G.P., Knapp, D. and Zarin, D. 2011. Temporal Variability of Forest Fires in Eastern Amazonia. *Ecological Applications.* **21**(7), pp.2397-2412.https://doi.org/10.1890/10-1168.1

Anderson, I.P. and Bowen, M.R. 2000. *Fire Zones and the Threat to the Wetlands of Sumatra, Indonesia.* Forest Fire Prevention and Control Project.

Applegate, G., Chokkalingam, U. and Suyanto, S. 2001. *The Underlying Causes and Impacts of Fires in South-East Asia—Final Report.*

Ardiansyah, M., Boer, R. and Situmorang, A.P. 2017. Typology of Land and Forest Fire in South Sumatra, Indonesia Based on Assessment of Modis Data. *IOP Conference Series: Earth and Environmental Science.* **54**, p012058

Barbosa, R.I. and Fearnside, P.M. 2005. Fire Frequency and Area Burned in the Roraima Savannas of Brazilian Amazonia. *Forest Ecology and Management.* **204**(2), pp.371-384.https://doi.org/10.1016/j.foreco.2004.09.011

Bowen, M.R., Bompard, J.M., Anderson, I.P., Guizol, P. and Gouyon, A. 2001. *Anthropogenic Fires in Indonesia: A View from Sumatra.* Huntington, New York: Nova Science Publishers.

Cahyono, B.E., Fearns, P. and McAtee, B. 2013. Application of Modis Data to a Decadal Study of Fire Hotspots and Climate Relationships over Riau Province Indonesia. *Asian Journal of Applied Sciences (ISSN: 2321-0893).* **1**(1),

Cattau, M.E., Harrison, M.E., Shinyo, I., Tungau, S., Uriarte, M. and DeFries, R. 2016a. Sources of Anthropogenic Fire Ignitions on the Peat-Swamp Landscape in Kalimantan, Indonesia. *Global Environmental Change.* **39**, pp.205-219.10.1016/j.gloenvcha.2016.05.005

Cattau, M.E., Marlier, M.E. and DeFries, R. 2016b. Effectiveness of Roundtable on Sustainable Palm Oil (Rspo) for Reducing Fires on Oil Palm Concessions in Indonesia from 2012 to 2015. *Environmental Research Letters.* **11**(10), p105007.10.1088/1748-9326/11/10/105007

Dennis, R.A. 1999. *A Review of Fire Projects in Indonesia (1982-1998).* Center for International Forestry Research (CIFOR).

Dennis, R.A., Hoffmann, A., Applegate, G., Gemmingen, G. and Kartawinata, K. 2001. Large-Scale Fire: Creator and Destroyer of Secondary Forests in Western Indonesia. *Journal of Tropical Forest Science.* **13**, pp.786-799

Dennis, R.A., Mayer, J., Applegate, G., Chokkalingam, U., Colfer, C., Kurniawan, I., Lachowski, H., Maus, P., Permana, R.P., Ruchiat, Y., Stolle, F., Suyanto and Tomich, T.P. 2005. Fire, People and Pixels: Linking Social Science and Remote Sensing to Understand Underlying Causes and Impacts of Fires in Indonesia. *Human Ecology.* **33**(4), pp.465-504.10.1007/s10745-005-5156-z

Elz, I., Tansey, K., Page, S.E. and Trivedi, M. 2015. Modelling Deforestation and Land Cover Transitions of Tropical Peatlands in Sumatra, Indonesia Using Remote Sensed Land Cover Data Sets. *Land.* **4**(3), pp.670-687.10.3390/land4030670

Eva, H. and Lambin, E.F. 1998. Remote Sensing of Biomass Burning in Tropical Regions. *Remote Sensing of Environment.* **64**(3), pp.292-315.10.1016/s0034-4257(98)00006-6

Eva, H. and Lambin, E.F. 2000. Fires and Land-Cover Change in the Tropics: A Remote Sensing Analysis at the Landscape Scale. *Journal of Biogeography.* **27**(3), pp.765-776

Fanin, T. and van der Werf, G.R. 2017. Precipitation–Fire Linkages in Indonesia (1997–2015). *Biogeosciences.* **14**(18), pp.3995-4008.10.5194/bg-14-3995-2017

Field, R.D. and Shen, S.S.P. 2008. Predictability of Carbon Emissions from Biomass Burning in Indonesia from 1997 to 2006. *Journal of Geophysical Research: Biogeosciences.* **113**(G4).10.1029/2008jg000694

Field, R.D., van der Werf, G.R., Fanin, T., Fetzer, E.J., Fuller, R., Jethva, H., Levy, R., Livesey, N.J., Luo, M., Torres, O. and Worden, H.M. 2016. Indonesian Fire Activity and Smoke Pollution in 2015 Show Persistent Nonlinear Sensitivity to El Nino-Induced Drought. *Proc Natl Acad Sci U S A.* **113**(33), pp.9204-9209.10.1073/pnas.1524888113

Field, R.D., van der Werf, G.R. and Shen, S.S.P. 2009. Human Amplification of Drought-Induced Biomass Burning in Indonesia since 1960. *Nature Geosci.* **2**(3), pp.185-188.http://www.nature.com/ngeo/journal/v2/n3/suppinfo/ngeo443_S1.html

Foster, D.R. 2002. Insights from Historical Geography to Ecology and Conservation: Lessons from the New England Landscape. *Journal of Biogeography.* **29**(10-11), pp.1269-1275.10.1046/j.1365-2699.2002.00791.x

Fuller, D.O. and Murphy, K. 2006. The Enso-Fire Dynamic in Insular Southeast Asia. *Climatic Change.* **74**(4), pp.435-455.10.1007/s10584-006-0432-5

Gaveau, D.L.A., Epting, J., Lyne, O., Linkie, M., Kumara, I., Kanninen, M. and Leader-Williams, N. 2009. Evaluating Whether Protected Areas Reduce Tropical Deforestation in Sumatra. *Journal of Biogeography.* **36**(11), pp.2165-2175.10.1111/j.1365-2699.2009.02147.x

Gaveau, D.L.A., Kshatriya, M., Sheil, D., Sloan, S., Molidena, E., Wijaya, A., Wich, S., Ancrenaz, M., Hansen, M., Broich, M., Guariguata, M.R., Pacheco, P., Potapov, P.V., Turubanova, S. and Meijaard, E. 2013. Reconciling Forest Conservation and Logging in Indonesian Borneo. *PLoS One.* **8**(8), pe69887.10.1371/journal.pone.0069887

Gaveau, D.L.A., Salim, M.A., Hergoualc'h, K., Locatelli, B., Sloan, S., Wooster, M., Marlier, M.E., Molidena, E., Yaen, H., DeFries, R., Verchot, L., Murdiyarso, D., Nasi, R., Holmgren, P. and Sheil, D. 2014. Major Atmospheric Emissions from Peat Fires in Southeast Asia During Non-Drought Years: Evidence from the 2013 Sumatran Fires. *Sci Rep.* **4**, p6112.10.1038/srep06112

Gaveau, D.L.A., Wandono, H. and Setiabudi, F. 2007. *Three Decades of Deforestation in Southwest Sumatra: Have Protected Areas Halted Forest Loss and Logging, and Promoted Re-Growth?*

Harrison, M.E., Ottay, J.B., D’Arcy, L.J., Cheyne, S.M., Anggodo, Belcher, C., Cole, L., Dohong, A., Ermiasi, Y., Feldpausch, T., Gallego-Sala, A., Gunawan, A., Höing, A., Husson, S.J., Kulu, I.P., Soebagio, S.M., Mang, S., Mercado, L., Morrogh-Bernard, H.C., Page, S.E., Priyanto, R., Ripoll Capilla, B., Rowland, L., Santos, E.M., Schreer, V., Sudyana, I.N., Taman, S.B.B., Thornton, S.A., Upton, C., Wich, S.A. and van Veen, F.J.F. 2019. Tropical Forest and Peatland Conservation in Indonesia: Challenges and Directions. *People and Nature.* **n/a**(n/a).10.1002/pan3.10060

Kirana, A.P., Sitanggang, I.S. and Syaufina, L. 2016. Hotspot Pattern Distribution in Peat Land Area in Sumatera Based on Spatio Temporal Clustering. *Procedia Environmental Sciences.* **33**, pp.635-645.https://doi.org/10.1016/j.proenv.2016.03.118

Langner, A., Miettinen, J. and Siegert, F. 2007. Land Cover Change 2002–2005 in Borneo and the Role of Fire Derived from Modis Imagery. *Global Change Biology.* **13**(11), pp.2329-2340.10.1111/j.1365-2486.2007.01442.x

Langner, A. and Siegert, F. 2009. Spatiotemporal Fire Occurrence in Borneo over a Period of 10 Years. *Global Change Biology.* **15**(1), pp.48-62.10.1111/j.1365-2486.2008.01828.x

Functions to Support Extension Education Program Evaluation. 2020. CRAN.

Margono, B.A., Potapov, P.V., Turubanova, S., Stolle, F. and Hansen, M.C. 2014. Primary Forest Cover Loss in Indonesia over 2000–2012. *Nature Climate Change.* **4**(8), pp.730-735.10.1038/nclimate2277

Miettinen, J., Shi, C. and Liew, S.C. 2010. Influence of Peatland and Land Cover Distribution on Fire Regimes in Insular Southeast Asia. *Regional Environmental Change.* **11**(1), pp.191-201.10.1007/s10113-010-0131-7

Nikonovas, T., Spessa, A.C. and Mezbahuddin, S. 2019. Forecasting Fire Activity in Indonesia as Function of Fire Weather and Land Cover Change [Abstract]. In: *EGU General Assembly 2019*, *7–12 April 2019, Vienna*. pp.EGU2019-8082.

Noojipady, P., Morton, D.C., Schroeder, W., Carlson, K.M., Huang, C., Gibbs, H.K., Burns, D., Walker, N.F. and Prince, S.D. 2017. Managing Fire Risk During Drought: The Influence of Certification and El Niño on Fire-Driven Forest Conversion for Oil Palm in Southeast Asia. *Earth System Dynamics.* **8**(3), pp.749-771.10.5194/esd-8-749-2017

Numata, I., Cochrane, M.A. and Galvão, L.S. 2011. Analyzing the Impacts of Frequency and Severity of Forest Fire on the Recovery of Disturbed Forest Using Landsat Time Series and Eo-1 Hyperion in the Southern Brazilian Amazon. *Earth Interactions.* **15**(13), pp.1-17.10.1175/2010EI372.1

Pan, X., Chin, M., Ichoku, C. and Field, R. 2018. Connecting Indonesian Fires and Drought with the Type of El Niño and Phase of the Indian Ocean Dipole During 1979–2016. *Journal of Geophysical Research: Atmospheres.* **123**.10.1029/2018JD028402

Plucinski, M.P. 2012. *A Review of Wildfire Occurrence Research*. Bushfire Cooperative Research Centre. Available from: http://www.bushfirecrc.com/sites/default/files/managed/resource/attachment_g_fire_occurrence_literature_review_0.pdf

Prasetyo, L.B., Dharmawan, A.H., Nasdian, F.T. and Ramdhoni, S. 2016. Historical Forest Fire Occurrence Analysis in Jambi Province During the Period of 2000 – 2015: Its Distribution & Land Cover Trajectories. *Procedia Environmental Sciences.* **33**, pp.450-459.10.1016/j.proenv.2016.03.096

Riitters, K., Wickham, J., Costanza, J.K. and Vogt, P. 2015. A Global Evaluation of Forest Interior Area Dynamics Using Tree Cover Data from 2000 to 2012. *Landsc Ecol.*

Riitters, K., Wickham, J., O'Neill, R., Jones, K., Smith, E., Coulston, J. and Smith, J. 2002. Fragmentation of Continental United States Forests. *Ecosystems.* **5**, pp.0815-0822.10.1007/s10021-002-0209-2

Riitters, K., Wickham, J., O’Neill, R., Jones, B. and Smith, E. 2000. Global-Scale Patterns of Forest Fragmentation. *Conserv Ecol.* **4**, Saji, N.H., Goswami, B.N., Vinayachandran, P.N. and Yamagata, T. 1999. A Dipole Mode in the Tropical Indian Ocean. *Nature.* **401**(6751), pp.360-363.10.1038/43854

Siegert, F., Ruecker, G., Hinrichs, A. and Hoffmann, A.A. 2001. Increased Damage from Fires in Logged Forests During Droughts Caused by El Nino. *Nature.* **414**(6862), pp.437-440.10.1038/35106547

Sitanggang, I.S. and Ismail, M.H. 2011. Classification Model for Hotspot Occurrences Using a Decision Tree Method. *Geomatics, Natural Hazards and Risk.* **2**(2), pp.111-121.10.1080/19475705.2011.565807

Sitanggang, I.S., Istiqomah, N. and Syaufina, L. 2018. Fire Spot Identification Based on Hotspot Sequential Pattern and Burned Area Classification. *BIOTROPIA.* **25**(3), pp.155-163.http://dx.doi.org/10.11598/btb.2018.25.3.676

Sitanggang, I.S., Yaakob, R., Mustapha, N. and Ainuddin, A.N. 2013. Predictive Models for Hotspots Occurrence Using Decision Tree Algorithms and Logistic Regression. *Journal of Applied Sciences.* **13**(2), pp.252-261.10.3923/jas.2013.252.261

Sloan, S., Locatelli, B., Wooster, M.J. and Gaveau, D.L.A. 2017. Fire Activity in Borneo Driven by Industrial Land Conversion and Drought During El Niño Periods, 1982–2010. *Global Environmental Change.* **47**, pp.95-109.https://doi.org/10.1016/j.gloenvcha.2017.10.001

Spessa, A.C., Field, R.D., Pappenberger, F., Langner, A., Englhart, S., Weber, U., Stockdale, T., Siegert, F., Kaiser, J.W. and Moore, J. 2015. Seasonal Forecasting of Fire over Kalimantan, Indonesia. *Natural Hazards and Earth System Science.* **15**(3), pp.429-442.10.5194/nhess-15-429-2015

Stolle, F., Chomitz, K.M., Lambin, E.F. and Tomich, T.P. 2003. Land Use and Vegetation Fires in Jambi Province, Sumatra, Indonesia. *Forest Ecology and Management.* **179**(1), pp.277-292.https://doi.org/10.1016/S0378-1127(02)00547-9

Stolle, F. and Lambin, E.F. 2003. Interprovincial and Interannual Differences in the Causes of Land-Use Fires in Sumatra, Indonesia. *Environmental Conservation.* **30**(4), pp.375-387.10.1017/S0376892903000390

Sumarga, E. 2017. Spatial Indicators for Human Activities May Explain the 2015 Fire Hotspot Distribution in Central Kalimantan Indonesia. *Tropical Conservation Science.* **10**, p1940082917706168.10.1177/1940082917706168

Sun, Q., Zhang, C., Liu, M. and Zhang, Y. 2016. Land Use and Land Cover Change Based on Historical Space–Time Model. *Solid Earth.* **7**(5), pp.1395-1403.10.5194/se-7-1395-2016

Syaufina, L. and Sitanggang, I.S. 2018. *Peatland Fire Detection Using Spatio-Temporal Data Mining Analysis in Kalimantan, Indonesia.*

Thonicke, K., Venevsky, S., Sitch, S. and Cramer, W. 2001. The Role of Fire Disturbance for Global Vegetation Dynamics: Coupling Fire into a Dynamic Global Vegetation Model. *Global Ecology and Biogeography.* **10**(6), pp.661-677

Turner, M.G. 2005. Landscape Ecology: What Is the State of the Science? *Annual Review of Ecology, Evolution, and Systematics.* **36**(1), pp.319-344.10.1146/annurev.ecolsys.36.102003.152614

Van der Laan, C., Verweij, P.A., Quiñones, M.J. and Faaij, A.P. 2014. Analysis of Biophysical and Anthropogenic Variables and Their Relation to the Regional Spatial Variation of Aboveground Biomass Illustrated for North and East Kalimantan, Borneo. *Carbon Balance and Management.* **9**(1), p8.10.1186/s13021-014-0008-z

Vetrita, Y. and Cochrane, M.A. 2020. Fire Frequency and Related Land-Use and Land-Cover Changes in Indonesia's Peatlands. *Remote Sensing.* **12**(1).10.3390/rs12010005

Yang, S. 2012. Study on Land Use Structural Change Based on Information Entropy. In: *Advances in Multimedia, Software Engineering and Computing Vol.2, 2012//, Berlin, Heidelberg*. Springer Berlin Heidelberg, pp.49-51.

Zhang, D. 2017. A Coefficient of Determination for Generalized Linear Models. *The American Statistician.* **71**(4), pp.310-316.10.1080/00031305.2016.1256839

Rsq: R-Squared for Generalized Linear (Mixed) Models 2020.

Chapter 6
Conclusions and Recommendations For Further Research

6.1 Conclusion

The aims of this research were to explore the spatial and temporal connections between fire, land cover, land cover change and tree cover loss, in order to better understand how agricultural and plantation management can be altered to minimize fire and associated environmental impacts.

The thesis has three primary research objectives :

1. Analyse the occurrence of fire and tree cover loss, as well as information on the extent of peat land, protected areas, and concessions to explore spatial and temporal relationships among forest, forest loss, and fire frequency in Riau Province, Indonesia.
2. Asses the association of fire with specific land cover transitions in Riau Province, Indonesia.
3. Create models of the fire risk in Riau Province, Indonesia using antecedent attributes such as hotspot, tree cover loss and land cover type.

Briefly, we find that fire in Riau is a factor of 6 greater in regions of forest loss compared to regions of no loss, indicating a close link between forest loss and fire (Cochrane, 2003). However, since fire frequency is lower after forest loss and similar to the rate before forest loss occurred then it appears that the fires contribute to loss of canopy cover. It has been suggested that cleared and burnt land is worth substantially more than land that had only been cleared (Page and Hooijer, 2016) and this seems to explain the economic driver why fires may start to decline in areas where all natural forest has already been converted.

Furthermore, assessing the association of fire with specific land cover transitions, we find that the greatest fire frequency in Riau province occurs in regions that have been converted from secondary peat swamp forest to shrub and plantation, confirming fire is often used to carry out land use changes (Tacconi et al., 2007). The involvement of land cover transitions with forest fires also shown in other previous work (Gaveau et al., 2014; Noojipady et al., 2017; Reiche et al., 2018). Our work has led us to recommend that protecting secondary forest from plantation development would reduce fire risk. In addition, since high fire frequency is also found in degraded landscapes covered by shrub then we promote peatland rewetting and revegetating to reduce the risk of fire (Harrison et al., 2019).

The detailed results of the thesis are described in three chapters and the main conclusions are outlined in the next sections.

6.1.1 Relationship Between Fire and Forest Cover Loss in Riau Province, Indonesia Between 2001 and 2012

In answer to the first objective, we have explored the relationship among fire, land-use, and land-cover change in Riau Province, Indonesia, over the period 2001 to 2012. We found that at the local (1 km) scale, fire and forest loss were closely related both spatially and temporally. The majority of fire in Riau occurs in regions that are also experiencing forest loss. This finding has important implications for forest management and fire suppression efforts in Riau. Those results are described in Chapter 3 and presented in published work (Adrianto et al., 2019). The important results are:

a) Hotspot density is a factor of three greater on peatlands compared to non-peatlands, i.e. 0.06 km^{-2} yr^{-1} versus 0.02 km^{-2} yr^{-1} (Section 3.3.1).
b) At the provincial level over the period 2001 to 2012, there was an insignificant change in the annual number of fire hotspots (−35 hotspots yr^{-1}), whilst the rate of tree cover loss increased significantly ($p<0.05$) by 186 km^2 yr^{-1} (Section 3.3.2).
c) At the local scale, the hotspot density in regions of forest loss was 0.138 km^{-2} yr^{-1}, a factor 6.5 greater than the hotspot density of 0.021 km^{-2} yr^{-1} in regions with no forest loss (Section 3.3.3).
d) In forested peatland areas, regions with tree cover loss experienced 8 times more fire hotspots that regions without tree cover loss. (Section 3.3.4).
e) Of all the different land-use types, wood fiber concessions had the highest proportional rate of forest loss (5.8% yr^{-1}) and the highest hotspot density (0.06 km^{-2} yr^{-1}), whereas protected areas experienced the lowest proportional forest loss (1% yr^{-1}) and hotspot density (0.018 km^{-2} yr^{-1}) (Section 3.3.5).
f) The “other” land use category, which was areas outside of concessions or protected areas, accounted for 44% of hotspots in peatland areas, and 53% of hotspot in non-peatland areas (Section 3.3.6).

g) In peatland areas, the hotspot density in oil palm and wood fiber concessions is more than a factor 100 greater than in logging concessions and a factor 10 greater than in protected areas (Section 3.3.7).
h) Logging concessions and protected areas exhibit strong correlations ($r^2 > 0.45$) between annual forest loss and fire in both peat and non-peat areas (Section 3.3.8).
i) Almost all (92%) of fire hotspots occurred in pixels that were forest in 2001 (> 50% forest cover in 2000) (Section 3.3.9).
j) Hotspots occurs in the same year as tree cover loss in 73% of cells, compared to 66% in non-peatlands (Section 3.3.10).

These results demonstrate the close link between forest loss and fire in Riau. We recommend that targeting fire suppression activities to areas of natural forest adjacent to areas with recent forest loss maybe be an effective way to prioritize fire suppression capacity in periods of high fire risk.

6.1.2 Forest and Land Fires are Mainly Associated with Deforestation in Riau Province, Indonesia

To address the second objective (asses the association of fire with specific land cover transitions), we combined a new land-cover dataset with information on the location and timing of fires from satellite imagery. We found that fire is closely connected to land-cover change, and that the majority of fire is associated with the transition of secondary forest to shrub and plantation The outcomes are explained in Chapter 4 and presented in published work (Adrianto et al., 2020). The main results are:

a) Between 1990 and 2017 there has been a steady decline in natural forest cover in Riau and an expansion of plantation, shrub and agriculture (Section 4.3.1).
b) Areas that experienced a conversion in land-cover type, experienced more frequent fire than areas that did not change land-cover, with the greatest frequency in regions that transition from secondary peat swamp forest to shrub or plantation with fire frequency of around 0.15 km^{-2} yr^{-1} . Areas that did not change land cover exhibit lower fire frequency, with shrub (0.06 km^{-2}) exhibiting a frequency of fire >60 times the frequency of fire in primary forest (Section 4.3.2).
c) Shrub areas which changed into plantation or agriculture had lower fire frequency after the land-cover transition. For land-cover transitions

involving conversion of secondary forest to shrub, the greatest fire frequency typically coincides with the timing of the land-cover transition (Section 4.3.3).

d) In shrub areas, the greatest fire frequency occurs in oil palm and wood fibre concessions. In secondary forests the greatest fire frequency also occurs in oil palm concessions. In shrub areas that were converted to plantation, the most frequent fires occur in oil palm concessions and areas of land outside of concessions or protected areas (Section 4.3.4).

Therefore, reducing the frequency of fire in Riau will require enhanced protection of secondary forests and restoration of shrub to natural forest. Reducing the susceptibility of the landscape to fire, through restoring, rewetting and revegetating degraded shrub, particularly on peatlands, is a priority.

6.1.3 Fire Hotspot Occurrences Modelling Based On Historical Hotspot, Tree Cover Loss And Land Cover Transition Between 2011 and 2019

In Chapter 5, we tried to develop models to estimate the number of hotspots between 2011-2019 in Riau Province, Indonesia using their previous years attributes such as hotspot, tree cover loss and land cover transition. Some important lesson are :

a) A one percent of tree cover loss in 25 km^2 cells increases the number of hotspot occurences by 56 with an increase of around 30 in non-peat area and almost 69 in peat land areas. Similarly, the increment of hotspot mean due to tree cover loss in peat land is double that in non-peat (Section 5.3.1 and 5.3.2).

b) The generalization of land-use transitions obscures specific transitions which have higher link to fire (Section 5.3.3) while weighting the land cover transitions by hotspot density gives a better result (Section 5.3.4).

c) It is beneficial to accommodate neighbourhood area characteristics in the model, regardless of whether you assume hotspots occurred spatially independently (Section 5.3.5).

6.2 Recommendations For Further Research

Based on our findings in Chapter 3, lower fire rates in protected areas and logging concessions on peatlands may be due to limited drainage and high canopy cover increasing soil moisture and reducing the potential for fire as well as a reduction in the potential for anthropogenic ignitions. Efforts to reduce fire need to address this underlying role of land-use and land-cover change in the occurrence of fire. Future work is required to demonstrate that restoration efforts can reduce fire.

Findings in Chapter 4 suggest that efforts to reduce fire in Indonesia need to focus on the link between land-cover change and fire**.** Future work needs to explore more about specific land-use transitions and relate these to occurrence of fire, for example fire-prone shrub.

Exploration of some models in Chapter 5 suggest analysis should include a time series of plantation concession maps with information on their status such as data of establishment, change permit or closure and condition of vegetation cover. In addition, we recommend future analysis should analyse the transition of secondary forest into plantation or shrub.

Bibliography

Adrianto, H.A., Spracklen, D.V. and Arnold, S.R. 2019. Relationship between Fire and Forest Cover Loss in Riau Province, Indonesia between 2001 and 2012. *Forests.* **10**(10).10.3390/f10100889

Adrianto, H.A., Spracklen, D.V., Arnold, S.R., Sitanggang, I.S. and Syaufina, L. 2020. Forest and Land Fires Are Mainly Associated with Deforestation in Riau Province, Indonesia. *Remote Sensing.* **12**(1).https://doi.org/10.3390/rs12010003

Cochrane, M.A. 2003. Fire Science for Rainforests. *Nature.* **421**(6926), pp.913-919.10.1038/nature01437

Gaveau, D.L.A., Salim, M.A., Hergoualc'h, K., Locatelli, B., Sloan, S., Wooster, M., Marlier, M.E., Molidena, E., Yaen, H., DeFries, R., Verchot, L., Murdiyarso, D., Nasi, R., Holmgren, P. and Sheil, D. 2014. Major Atmospheric Emissions from Peat Fires in Southeast Asia During Non-Drought Years: Evidence from the 2013 Sumatran Fires. *Sci Rep.* **4**, p6112.10.1038/srep06112

Harrison, M.E., Ottay, J.B., D’Arcy, L.J., Cheyne, S.M., Anggodo, Belcher, C., Cole, L., Dohong, A., Ermiasi, Y., Feldpausch, T., Gallego-Sala, A., Gunawan, A., Höing, A., Husson, S.J., Kulu, I.P., Soebagio, S.M., Mang, S., Mercado, L., Morrogh-Bernard, H.C., Page, S.E., Priyanto, R., Ripoll Capilla, B., Rowland, L., Santos, E.M., Schreer, V., Sudyana, I.N., Taman, S.B.B., Thornton, S.A., Upton, C., Wich, S.A. and van Veen, F.J.F. 2019. Tropical Forest and Peatland Conservation in Indonesia: Challenges and Directions. *People and Nature.* **n/a**(n/a).10.1002/pan3.10060

Noojipady, P., Morton, D.C., Schroeder, W., Carlson, K.M., Huang, C., Gibbs, H.K., Burns, D., Walker, N.F. and Prince, S.D. 2017. Managing Fire Risk During Drought: The Influence of Certification and El Niño on Fire-Driven Forest Conversion for Oil Palm in Southeast Asia. *Earth System Dynamics.* **8**(3), pp.749-771.10.5194/esd-8-749-2017

Page, S.E. and Hooijer, A. 2016. In the Line of Fire: The Peatlands of Southeast Asia. *Philos Trans R Soc Lond B Biol Sci.* **371**(1696), p20150176.http://dx.doi.org/10.1098/rstb.2015.0176

Reiche, J., Verhoeven, R., Verbesselt, J., Hamunyela, E., Wielaard, N. and Herold, M. 2018. Characterizing Tropical Forest Cover Loss Using Dense Sentinel-1 Data and Active Fire Alerts. *Remote Sensing.* **10**(5).10.3390/rs10050777

Tacconi, L., Moore, P.F. and Kaimowitz, D. 2007. Fires in Tropical Forests – What Is Really the Problem? Lessons from Indonesia. *Mitigation and Adaptation Strategies for Global Change.* **12**(1), pp.55-66.10.1007/s11027-006-9040-y