ELSEVIER

Forest Ecology and Management 179 (2003) 277–292

Forest Ecology and Management

www.elsevier.com/locate/foreco

Land use and vegetation fires in Jambi Province, Sumatra, Indonesia

F. Stolle*, K.M. Chomitz, E.F. Lambin, T.P. Tomich

Department of Geography, Université Catholique de Louvain, Place Louis Pasteur 3, B-1348 Louvain-La-Neuve, Belgium

Received 19 October 2001; received in revised form 15 July 2002; accepted 7 October 2002

Abstract

In Indonesia, vegetation fires occur every year in the dry season. To determine where and why fires occur, the natural and cultural landscape features that influence the location of fires were analysed. We investigated the probability of fire occurrence as a function of predisposing conditions and ignition sources, such as land use, land use zoning, accessibility or land cover, to understand the spatial determinants of fires. The study area is the entire province of Jambi, central Sumatra, Indonesia. This province has a diverse setting of actors (small- and large-holders), land cover types and land uses. Fires were extracted for 1992/1993 from National Oceanic Atmospheric Administration's Advanced Very High Resolution Radiometer (NOAA-AVHRR) satellite data. The results of the spatial statistical analysis show that fire occurrence in Jambi Province in 1992/1993 was determined both by predisposing conditions (mostly climate, elevation and suitability for specific tree crops) and human-related causes (presence of transmigration projects and land allocation to specific land uses). National policies are thus a major driving forces of fires through land allocation. Road accessibility is only an important determinant of fires in forests. Few fires seem to be accidental. While logging companies control fire during their exploitation of concessions, logged-over forests and forests allocated to production but not yet under use have many fires. In 1992/1993, large- and small-holders were likely to be both responsible for fire occurrence. These results highlight the large influence of land use and policies on vegetation fires in Indonesia.

© 2002 Elsevier Science B.V. All rights reserved.

Keywords: Fire; Land use; Biomass burning; Forest; Indonesia; Jambi

1. Introduction

Vegetation fires are a normal phenomenon in Indonesia. They occur every year in the dry season and are characteristic of wet tropical forest ecosystems (Goldammer and Siebert, 1990). Fires can occur naturally or can be used as a tool to clear land for agricultural purpose (e.g. forest to plantation). As an exceptional event, large vegetation fires raged throughout the Indonesian archipelago in 1997 and 1998, causing a smog blanket covering over 3 million km^2 (Stolle and Tomich, 1999), with economic losses estimated at over 4.5 billion US$ (Schweithelm et al., 1999). Blame was put on the combination of dry conditions caused by El Niño and the frequent use of fire by large- and small-holders to clear land. This made clear that the use of fires needs to be regulated, especially during dry years. This requires a good preliminary understanding of the causes of burning, and of the natural and cultural landscape features that influence the location of fires. Identifying

* Corresponding author. Tel.: +32-10-474-477; fax: +32-10-472-877.
E-mail address: stolle@geog.ucl.ac.be (F. Stolle).

0378-1127/02/$ – see front matter © 2002 Elsevier Science B.V. All rights reserved.
PII: S0378-1127(02)00547-9

the proximate causes of fires would help to understand why and when people use fires.

The objective of this study is to understand the major spatial determinants of fires in a normal (non-El Niño) year to infer the underlying causes of biomass burning in the Jambi Province, Sumatra. The main emphasis of this paper is on social, economic and political factors which determine fire occurrence. The study aims at addressing six specific questions: (i) Where are fires taking place? (ii) Is forest more threatened by fires than other land cover types? (iii) Does accessibility play a major role in fire occurrence? (iv) Are small-holders or large-holders mainly responsible for fire occurrence? (v) What is the influence of current land use on fire occurrence? (vi) Do government policies on land allocation play an important role in determining vegetation fires? First, a conceptual model was built to represent our current understanding of the interactions between fires, landscape factors and land managers. Second, measurable proxy variables were identified to represent the processes and actors identified in the conceptual model. Third a cross-table analysis between fires and landscape variables was conducted to analyse the spatial associations between fires and landscape attributes. Fourth, a multivariate logistic regression model was developed to quantify the relations between landscape attributes and fire occurrence. Further, more specific regressions were developed to focus on specific land cover types.

2. Background

The causes of fires in the wet tropics have been described by many authors (Malingreau et al., 1985; Goldammer and Siebert, 1990; Crutzen and Goldammer, 1993; Barber and Schweithelm, 2000; Giri and Shrestha, 2000). Several studies have also documented the strong spatial association between fires and land use changes (Fujisaka et al., 1996; Ehrlich et al., 1997; Eva and Lambin, 2000). Fire has been frequently documented as a deliberate tool for land conversion. Examples are found all across the tropics, e.g. tropical forest conversion for pasture in Brazil (Fearnside, 1983; Fujisaka et al., 1996), clearing for plantations in Africa (Ataga et al., 1986) and clearing savannahs for agriculture (Allen, 1986). Accidental fires of anthropogenic origin (i.e. escaping from agriculture) have also been responsible for the destruction of the natural vegetation, notably in dry years, e.g. in Borneo (Malingreau et al., 1985; Goldammer, 1999). In the Amazon, the occurrence of fire entering into the moist forests becomes more likely when selective logging has been undertaken (Holdsworth and Uhl, 1997; Nepstad et al., 1997) leading to degradation of considerable areas of forest (Nepstad et al., 1999) and creating a positive feedback, where fire-affected forest becomes more prone to subsequent fires and degradation (Cochrane et al., 1999). Under normal climatic conditions, unlogged humid forests remain essentially immune from fire attacks. By contrast, open forests experience a shorter fire return interval (Phillips, 1974; Huckabay, 1989; Swaine, 1992). Thus, fire is often cited as a major disturbance factor in the tropics.

Multivariate statistical analysis has been widely used in land use/cover change studies (Ludeke et al., 1990; Chomitz and Gray, 1996; Walsh et al., 1999; Mertens and Lambin, 2000). Chomitz and Gray (1996) provide a theoretical basis for these analyses, elaborating the classical model of von Thünen and Ricardo (von Thünen, 1826). Their model posits first, that the value of a parcel of land in a particular land use is a function of the parcel's characteristics (particularly market access and agronomic potential); and second, that each parcel is devoted to the use with the highest value. The model can be used to predict the probability that forest land with specified characteristics is converted to other cover types. In this study, the approach is slightly different since the object of study is fire occurrence. The theoretical framework is however identical as many fires are used as a tool for land clearing. This technique has proven that it can detect determinants of fires in large data sets (Vega Garcia et al., 1995). Multivariate models allow us to quantify the effect of different landscape characteristics on the location-specific risk of fire.

2.1. Conceptual model

The conceptual model represents fire occurrence as resulting from the combination of predisposing conditions and trigger factors for ignition (Fig. 1). Some of the predisposing conditions that increase the chance of fire occurrence are low rainfall, presence of logged-over forest or grassland as land covers, and dry peat

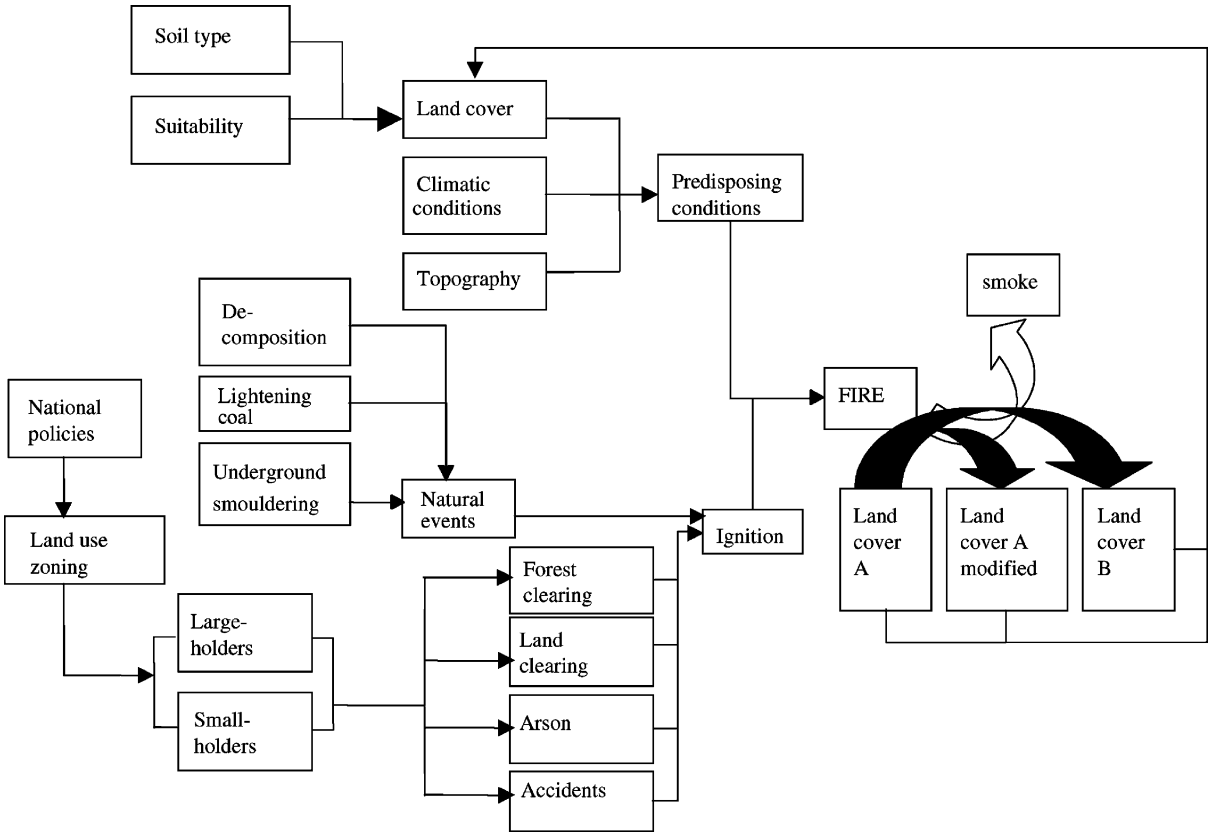


Fig. 1. Conceptual model of fire occurrence. The upper part of the figure represents the predisposing conditions for fire. The lower part shows the pathways for ignition of fires in four levels: proximate causes, human actions and natural events, land use zoning, and national policies.

soils. Ignition results from human-related activities or natural events. Purely natural events that can cause fires are lightning and heat generated by decomposition resulting in smouldering and then flaming combustion. Surface fires can also be ignited, under extremely dry conditions, by long-smouldering underground coal seams (Prakash and Gupta, 1999). Human-related fires can have a range of causes: accidental fires, arson and land clearing. The accidental ignition of an area can be caused by careless use of fire, e.g. from cigarettes, camp fires or by fires escaping from a plot where it was used for land clearing. All these ignition sources can be the consequence of acts from small- or large-holders. In Indonesia, the areas occupied by small- or large-holders are in part determined by land use zoning defined by national policies. The conceptual model (Fig. 1) illustrates these different levels of causes of fire.

Fire is virtually the only tool used for conversion of land in Indonesia. Landholders first slash the vegetation and let it dry. After 1 or 2 months the area is then burned. If necessary a second burn is used. Both small-holders and large-holders use fire to clear land, although large companies may slash by mechanised means. The conversion of land can be from forest, logged-over forest or secondary vegetation to small-holder farming areas or large-holder plantations. Fires in Indonesia are sometimes related to disputes between small-holders and large-holders on land use rights (Bompard and Guizol, 1999; Bowen et al., 1999; Gouyon, 1999). Small-holders who have been chased away from their land can take revenge by burning new plantations of large-holders. Large-holders can also burn outside their concession to destroy small-holder crops and get easier or cheaper access to that land.

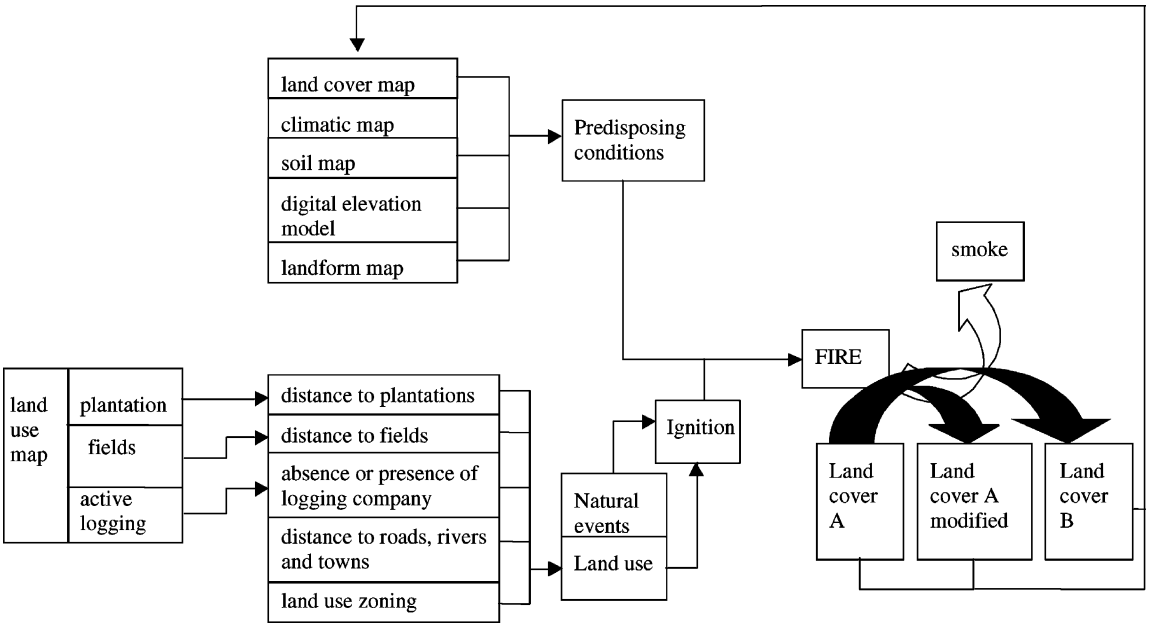


Fig. 2. Reduced-form model of fire occurrence. The figure shows the data used and causal relationships with fire. The upper part of the figure shows the proxy data used to represent predisposing conditions. The lower part shows the proxy data used to represent factors leading to fire ignition.

Not all the causes and agents of fires represented on the conceptual model can be easily represented by measurable, spatially-explicit variables. Therefore, to construct a reduced-form model, zones or distance variables which represent these different causes and predisposing conditions were identified (Fig. 2). Spatial locations were thus used as proxies for explanatory factors of fires.

Accidental fires are likely to occur in accessible areas. High accessibility will give a higher chance of unintended start of a fire, that is, close to rivers, roads, towns, small-holder fields, plantations and active logging concessions. Of course, the accidental fire zone overlaps with the intentional fire zone and these two categories of fire cannot be distinguished remotely. Clearing by small-holders takes place in and around the zone already used by small-holders. In the small-holder zone, clearing can be used for agricultural expansion, to clear old crops or to burn agricultural residues. Other possible expansion areas are logged-over or natural forests. Large-holder clearing will generally not take place inside the planted area but around it. Conflict over land often arises due to overlapping land claims between large- and small-holders.

3. Study area

The study area is the province of Jambi, central Sumatra, Indonesia (Fig. 3). This province has a diverse setting of people (small- and large-holders, new settlers and long settled farmers), land covers (Fig. 4) and land uses (plantations, logging concessions, national parks, small-holder farming and others). The province covers 50 million ha with, in the eastern part, the hills of Kerinci with altitudes up to 3000 m and, in the western part, large swamp areas. The population was 2 million in 1990 (BPS, 1992) and almost entirely rural. The main city, Jambi City, on the western edge of the swamp area, has a population of 300,000 (BPS, 1992). The main river is the Batang Hari, which flows from east to west through the province. In the 1980s, the trans-Sumatra highway connected the eastern and western parts of Jambi. After the introduction of the *Hevea brasiliensis* rubber tree at the start of the 20th century, farmers had an extra incentive to settle near rivers to transport rubber to the markets. Rubber trees, cultivated both by small-holders and large-holders, and oil-palm in large plantations have expanded recently, especially along newly constructed roads.

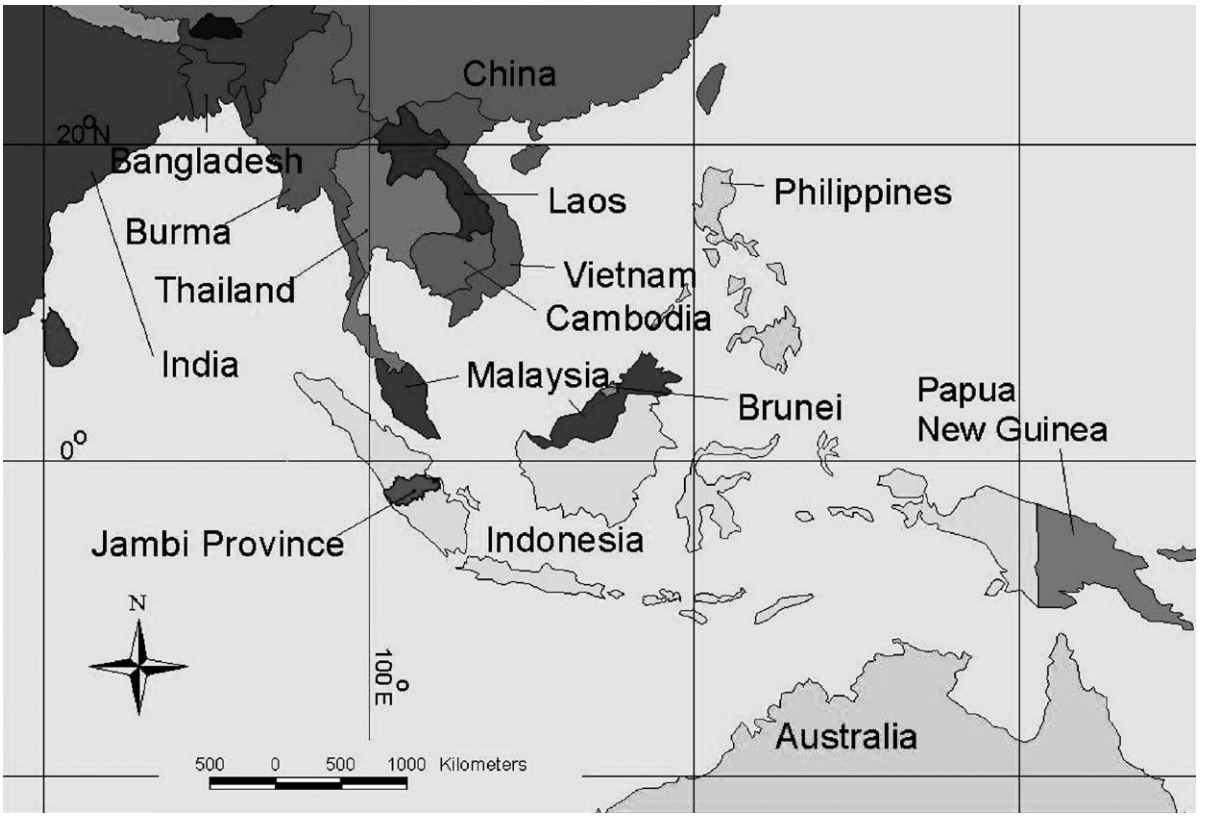


Fig. 3. Location of Jambi Province in southeast Asia.

Over two thirds of the province has been designated as forestry land and zoned to specific land uses by the Ministry of Forestry and Estate Crops (MOFEC). In the mid-1980s, large zones were designated to logging and plantation concessions. Outside the MOFEC designated areas, large transmigration projects were developed. This resulted in rapid land-cover changes in the province. The main land uses today are selective logging, plantations (oil-palm and timber), national parks and small-holder rubber farming.

4. Data

The dependent variable, fire occurrence in 1992/1993, was extracted from the 1992/1993 database of fires from the European Space Agency (ESA, 1997), which is based on remote sensing data from NOAA-AVHRR (National Oceanic Atmospheric Administration's Advanced Very High Resolution Radiometer) sensor. This satellite was developed for weather and oceanic purposes, but can also be used for fire monitoring. The NOAA-AVHRR sensor has several infrared bands which are used to detect fires using a contextual detection algorithm (Flasse and Caccato, 1996). The spatial resolution of the NOAA-AVHRR data is 1.1 km^2, which is also the resolution of the fire database. However, 50 m × 50 m fires can be detected given their high temperature. So both large and very small but hot fires are identified. Only a sample of all fires are detected: those that are taking place at the time of satellite overpass and under clear sky conditions (Eva and Lambin, 1998). The fire database identifies 136 fire pixels in the province for 1992/1993. The geolocation error of the NOAA-AVHRR data in Indonesia is around 2 km in average (Siegert and Hoffmann, 2000). Therefore, all pixels in a 2 km radius around observed fire points were labelled as potential fire pixels (total of 1111 potential fire pixels). Only the 1992/1993 burning season was chosen for

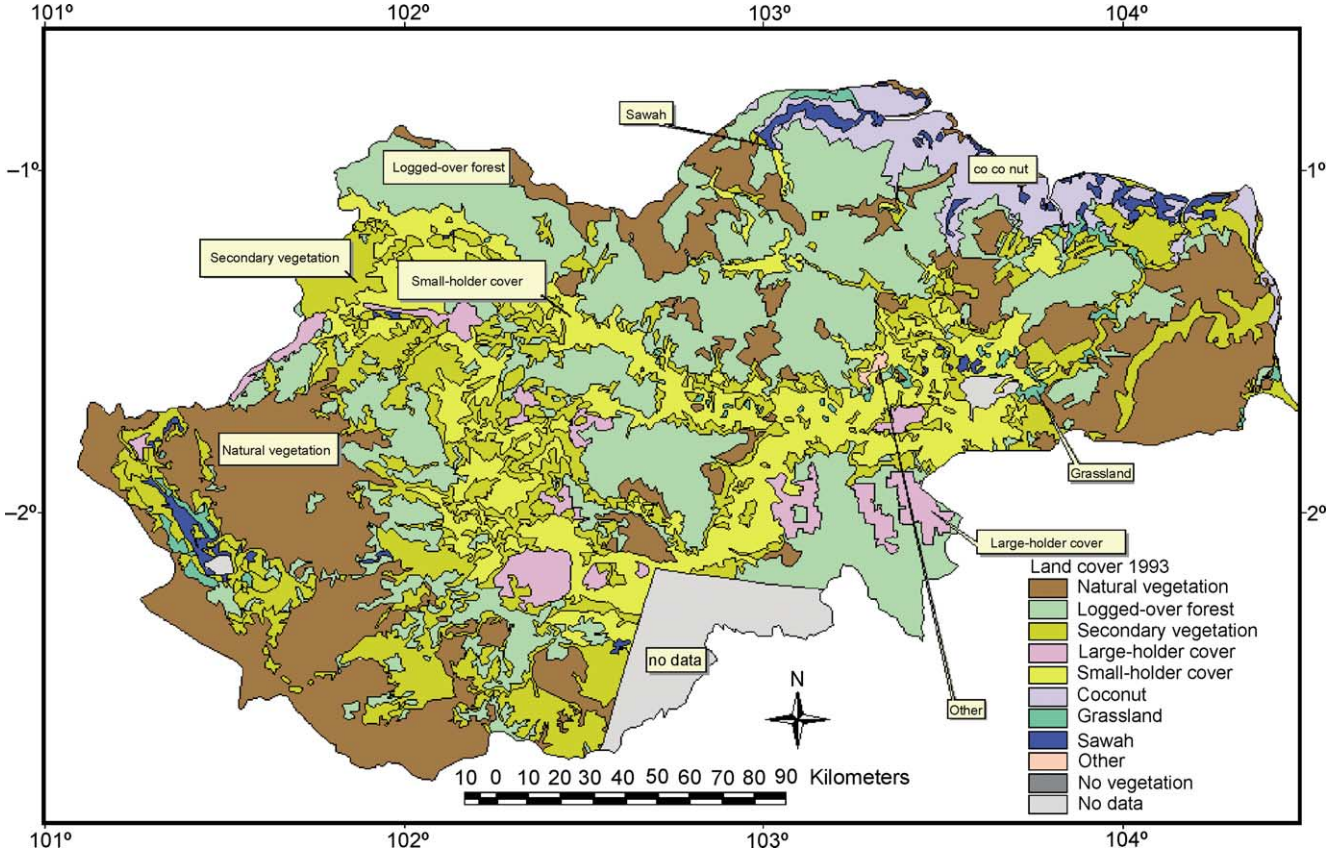


Fig. 4. Land cover of Jambi Province in 1993, adapted from BIOTROP.

this study because an accurate and detailed land use/cover map existed for that year, therefore allowing an analysis of the influence of land use/cover on fire occurrence. It was felt that working with reliable and simultaneous land use and fire data was more important than working with very recent data.

Data on the independent variables were all collected from Ministries of Indonesia and other national and international institutions:

- Tarmac roads digitised from the Ministry of Transportation, Jambi Province.
- Rivers from Digital Chart of the World (ESRI, 1993).
- Towns from Digital Chart of the World (ESRI, 1993).

Three categorical distance variables were derived from these data layers: distance to towns and roads with five categories (1–5, 5–10, 10–15, 15–20 and more than 20 km) and distance to rivers with three categories (1–5, 5–10 and more than 10 km):

- Zoned forestry land use, as determined by MOFEC of Indonesia in 1980. This is based on the so-called "agreed forest use" categories (Tata Guna Hutan Kesepakatan—TGHK): outside forestry zone (not allocated), protection forest (including limited production, protection and national park zones), production forest and conversion forest. Areas already under logging concession were excluded from the production zone and areas already converted to plantation (as derived from the land use map) were excluded from the conversion zone. This allowed comparison of allocation zones not yet used with areas already used by large-holders. In total, this land area governed by MOFEC covers about 70% of Jambi Province.
- Presence of transmigration projects (source map from Ministry of Transmigration of Indonesia, 1998). In most cases, this map represents the actual presence of transmigrants. However, in a few cases, transmigrants have abandoned the site or may have never arrived.
- Presence of large-holder logging concessions, derived from concession maps that include the granting date of the concession (source map from MOFEC Indonesia, 1998).
- Actual land use/cover. The term *land use* refers to the purposes for which humans exploit the land cover while *land cover* refers to the attributes of a part of the earth's land surface and immediate subsurface, including biota, soil, topography, surface and groundwater, and human structures. The map used was derived from fine spatial resolution Landsat TM satellite data (1993) and mixes land use and land cover categories. It identifies 18 classes which were aggregated for this study in 10 classes (Table 1). The land cover classes are also a proxy for fuel variables which are an important determinant of fires. A table of correspondence was established between land use/cover types and fuel load, expressed in biomass density, and seasonal fuel moisture which controls flammability (Table 2).
- Distances to small-holder fields and large-holder areas. This continuous variable was split into two categories: less than 5 km and more than 5 km from areas currently under use.
- Land system, which describes the landform (RePPProT, 1988) and identifies plains, swamps and other landforms. "Other landform" is a combination of the following classes: slopes, hills, plateau and terraces.
- Climate, sub-dividing Jambi Province into three regions: a wet area (3500–4300 mm of annual rainfall), a medium wet area (2500–3100 mm of annual rainfall) and a drier area (1800–2200 mm of annual rainfall) (RePPProT, 1988).

Table 1
Reclassification of land cover data from BIOTROP (1993)

BIOTROP classification	Reclassification
Natural vegetation	Natural vegetation
Sawah or tidal rice	Sawah
Coconut plantation	Coconut
Grasslands	Grasslands
Logged-over forest	Logged-over forest
Secondary vegetation	Secondary vegetation
Small-holder rubber	Small-holder land use
Secondary/food mosaic	Small-holder land use
Homesteads	Small-holder land use
Food crop mosaic	Small-holder land use
Rubber plantation	Large-holder land use
Oil-palm plantation	Large-holder land use
Tree crop mosaic	Large-holder land use
Tea plantation	Large-holder land use
Oil/rubber plantation	Large-holder land use
Other	Other
No data	No data

Table 2
Potential fuel load and moisture condition per land use/cover. Biomass data adapted from IC-SEA (1999). Fuel moisture description adapted from Whitten et al. (2000) and Laumonier (1997)

Land use/cover	Potential fuel load (biomass, t/ha)	Fuel moisture
Forest	520–940	Evergreen moist conditions
Secondary vegetation	65–230	Mix of evergreen and deciduous trees, several strata of trees, but with gaps thus more wind and more light than forest and thus more vulnerable to dry conditions
Logged-over forest	120–160	Mix of evergreen and deciduous trees, several strata of trees, but with gaps thus more wind and more light than forest and thus more vulnerable to dry conditions
Large-holder plantation	83–152	Very open forest, one strata easy to dry out because of more exposure to sun and wind
Small-holder rubber	15–80	Mix of evergreen and deciduous trees, several strata of trees, but with gaps thus more wind and more light than forest and thus more vulnerable to dry conditions
Grassland	3–8	No shadow, dry conditions

- Suitability maps for four tree crops (rubber, oil-palm, acacia and mango), with three categories: very suitable, suitable and non-suitable. Suitability for rubber is important for small- and large-holders alike while suitability for oil-palm and acacia is only important for large-holders since small-holders do not exploit these trees. Suitability for mango trees is only important for small-holders. These data came form the National Master Plan for Forest Plantations (MOFEC, 1993) and were derived from soil maps.

The different land use data sets are not always mutually exclusive, e.g. areas designated to transmigration could be located inside logging concessions and vice versa. Further, the actual land use does not always match with the land allocation, e.g. logging concessions may be found outside production forest. Finally, areas allocated to a certain use are not always already under that use. Therefore, the categories which were not mutually exclusive were defined as separate variables rather than as different categories of one variable.

5. Method

All these digital maps were geographically linked and rasterized with a pixel size of 1 km. To minimise spatial autocorrelation and maintain independence between observations, a 10% random sample of pixels was extracted, resulting in 4683 independent observations that included 111 fire pixels. Statistical analyses were carried out to test relationships between the independent variables representing landscape and land use factors, and fire occurrence. First, bivariate relationships were analysed with a cross-table. Second, multivariate relationships were modelled by logistic multiple regression, in the statistical software package SAS (1997). A small number of categories of variables with 0 fire points were excluded from the model resulting in 42 variables being included in the full model (Table 3). Categories with no fire were excluded due to statistical limitations of the logistic regression procedure that cannot handle categories with no dependent data. However, these categories were included in the frequency analysis.

The logistic regression estimates the parameters of a multivariate model in situations where the dependent variable is dichotomous (e.g. occurrence or non-occurrence of fires) and the independent variables are continuous or categorical. The logistic model has the form

$$\text{Logit}(P) = \log\left[\frac{P}{1-P}\right] = \alpha + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n \quad (1)$$

where P is the probability that a fire occurs, α the intercept and β_n are slope parameters associated with independent variables X_i (Hosmer and Lemeshow, 1989). The probability values can be quantitatively expressed in terms of independent variables by

$$P = \frac{\exp(\alpha + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n)}{1 + \exp(\alpha + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n)} \quad (2)$$

Table 3
Cross-table of fire occurrence in pixels (1 km^2) per category, total size of category, fire density per category, and categories excluded from multivariate statistical analysis

	Categories	Fire		Total area of class (pixels)	Fire density (number of fires/total area × 100)	Excluded from the multivariate analysis
		Number of pixels without fire	Number of pixels with fire			
Predisposing conditions						
Vegetation	Natural forest	1217	8	1225	0.65	
	Rice fields	77	0	77	0.00	x
	Coconut	179	3	182	1.65	x
	Grasslands	38	0	38	0.00	x
	Logged-over forest	1487	59	1546	3.82	
	Secondary vegetation	824	13	837	1.55	
	Small-holder land cover	991	23	1014	2.27	
	Large-holder plantation	156	8	164	4.88	
	Other	4	0	4	0.00	x
	No data	179	2	181	1.10	x
Eco-climate	Rainfall, 2500–3000 mm	3205	44	3249	1.35	
	Rainfall, 1800–2200 mm	1947	72	2019	3.57	
Suitability oil-palm	Very suitable	46	0	46	0.00	x
	Suitable	4063	95	4158	2.28	
	Not suitable	1043	21	1064	1.97	
Suitability rubber	Very suitable	3335	83	3418	2.43	
	Suitable	1049	18	1067	1.69	
	Not suitable	768	15	783	1.92	
Elevation (m)	0–100	2649	91	2740	3.32	
	100–300	1326	23	1349	1.70	
	300–3000	1177	2	1179	0.17	
Landform	Swamp	690	17	707	2.40	
	Plain	2211	84	2295	3.66	
	Other	2251	15	2266	0.66	
Forest allocation	Protected	1524	15	1539	0.97	
	Conversion	774	44	818	5.38	
	Production	1108	33	1141	2.89	
	Not allocated	1746	24	1770	1.36	
Transmigration	Absence	5067	105	5172	2.03	
	Presence	85	11	96	11.46	
Logging concession	Absence	3110	74	3184	2.32	
	Logging concession	1528	37	1565	2.40	
Accessibility						
Distance to roads (km)	1–5	1413	35	1448	2.42	
	5–10	1030	22	1052	2.09	
	10–15	724	31	755	4.11	
	15–20	575	18	593	3.04	
	>20	1410	10	1420	0.70	
Distance to towns (km)	1–5	972	13	985	1.32	
	5–10	1774	46	1820	2.53	
	10–15	1270	27	1297	2.08	

Table 3 (*Continued*)

	Categories	Fire		Total area of class (pixels)	Fire density (number of fires/total area × 100)	Excluded from the multivariate analysis
		Number of pixels without fire	Number of pixels with fire			
	15–20	659	25	684	3.65	
	>20	477	5	482	1.04	
Distance to rivers (km)	1–5	4208	86	4294	2.00	
	5–10	738	29	767	3.78	
	>10	206	1	207	0.48	
Distance to large-holder (km)	1–5	625	24	649	3.70	
	>5	4527	92	4619	1.99	
Distance to small-holder (km)	1–5	3987	101	4088	2.47	
	>5	1165	15	1180	1.27	
Land use						
Land use small-holder zone	Outside	2559	56	2615	2.14	
	Inside	2593	60	2653	2.26	
Land use large-holder zone	Absence	5006	109	5115	2.13	
	Presence	146	7	153	4.58	

$$\text{Odds(fire occurrence)} = \exp(\alpha + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_n X_n) \quad (3)$$

The odds is the ratio of the probability that some event will occur (fire in this case) divided by the probability that the same event will not occur (Kleinbaum et al., 1998). The odds ratio is then the ratio of two odds in which two groups of individuals are compared (Menard, 1995), e.g. the ratio of odds of fire in dry eco-climate zone and the odds of fire outside the dry eco-climatic zone. The odds ratio is thus always relative.

One measure of the model's goodness of fit is the pseudo-R^2 or ρ^2, defined as (Wrigley, 1985)

$$\rho^2 = 2\left[1 - \frac{\log[\beta]}{\log[c]}\right] \quad (4)$$

where β is the log likelihood of the model with intercept and covariance of all the variables and c the log likelihood of the model with the intercept only. Values of ρ^2 between 0.2 and 0.4 should be considered as a good fit. Before estimating the model, preliminary statistical tests were conducted on the independent variables. The data was tested for multicolinearity by the correlation matrix of the estimates. No independent variable had to be excluded as the Pearson correlation coefficient between independent variables was at most 0.75.

6. Results

The cross-table (Table 3) shows that some variables have much higher fire occurrence than others. Note that categories with less than 100 points were excluded from this analysis. Especially logged-over forest and conversion forests show high fire numbers while transmigration areas, which represent a much smaller area, show high fire densities. More than 50% of fires detected in 1992/1993 were in logged-over forests, which cover 30% of the total area. Fires were detected in more than 10% of all transmigration areas. Few or no fires were detected in natural forests, rice fields, coconut areas, grasslands, large-holder areas and other vegetation types. This indicates that fires are not randomly distributed and are likely to be of anthropogenic origin.

The overall explanatory power of the logistic regression model is fair with a $\rho^2 = 0.18$. The independent variables included in the model thus describe

Table 4
Prediction table of fire occurrence resulting from the full logistic regression for Jambi Province, in percentages of pixels

Percentages ($P = 0.01$, $n = 4749$)	Predicted		
	Fire	No fire	Total
Actual			
Fire	84	16	
No fire	49	51	
Total correct			52

fairly well the spatial distribution of fires. The predictability of fire occurrence was tested. The classification table probability is customarily set at 0.5 but is arbitrary and depends on the objective of the model. The choice of a probability level is a trade-off between correctly classifying true and false fires (Schuster, 1983; Jannick and Beckett, 1987). Here, we put the probability decision rule at 0.01. This low probability is chosen close to the actual probability of fires in the year 1992/1993 (i.e. 136 NOAA fire points out of a total of 49,000 pixels in Jambi Province). The classification (Table 4) shows that the model predicts 52% of the fires correctly. However, it gives a high rate of false positives, which is not surprising given the scattered pattern of fires in the landscape.

The full logistic model includes 16 variables with, in total, 39 categories. From these, nine categories are significant at the 0.05 level (Table 5). The odds ratio shows the increase or decrease of fire odds compared to a reference category for the same variable (Table 5). Land allocation through national policies plays a significant role in fire occurrence. From the nine significant categories, four represent directly or indirectly land allocation. The strongest influences on fire occurrence are the presence of transmigration projects, land allocation to production and conversion, and the absence of logging concessions. The presence of a transmigration area increases the odds of fire almost four times. 30% of the transmigration sites are relatively new (allocated less than 5 years ago) and thus fires are set in these transmigration areas to clear vegetation for the new settlers. Allocation to production area increases the odds of fire almost three times compared to areas outside the forest allocation zone. The allocation to production zone excludes the areas already under logging concessions and is thus mainly made of unoccupied forested land. The increase of fire probability in these areas is unlikely to be caused by natural fires, since natural forests are known to be fire resistant. Also, the natural forest land cover is not a significant category in the model. Since the unoccupied area is not used yet, but is zoned to be used in the future, this area might be very attractive to extension for large-holder plantations or small-holders.

The presence of active logging companies decreases the odds of fire 0.6 times. Fires and agricultural

Table 5
Significant parameters ($P < 0.05$) of the full logistic regression model for Jambi Province, with odds ratio and the reference category of the odds ratio ($\rho^2 = 0.18$ and Wald test $\beta \leq 0.0001$)

Significant variables		Estimate	Error	χ^2	$P > \chi^2$	Odds ratio	Compared to
	Intercept	−5.05	0.52	94.76	<0.0001		
Allocation	Logging concession	−0.25	0.12	4.55	0.033	0.6	Absence of logging concessions
	Presence of transmigration project	1.30	0.39	11.29	0.0008	3.7	Absence of transmigration
	Allocated as production area	0.54	0.22	6.20	0.0128	3.4	Not allocated zone
	Allocated as conversion area	0.40	0.18	5.06	0.025	3.0	Not allocated zone
Accessibility	Distance to small-holder area, 1–5 km	0.33	0.17	3.66	0.05	2.0	Distance to small-holder area, >5 km
	Distance to towns, 15–20 km	0.58	0.22	6.80	0.009	2.5	Distance to towns, >20 km
Predisposing	Eco-climate is dry (rainfall between 1800 and 2200 mm)	0.40	0.13	9.67	0.0019	2.2	Eco-climate is medium wet (rainfall between 2500 and 3000 mm)
	Suitable for rubber	0.91	0.31	8.20	0.0042	5.7	Unsuitable for rubber
	Elevation from 0 to 100 m	0.69	0.30	5.24	0.022	3.5	Elevation between 300 and 3000 m

expansion are thus mainly taking place outside areas used by logging companies. The allocation to conversion area increases the fire odds three times compared to non-allocated forest. This is consistent with the policy to allow clearing for plantations in the areas allocated to conversion. Although the conversion zone is mainly meant for large-holder plantations, the high fire probability in these areas can also be associated with agricultural expansion by small-holders.

There is no evidence that large-holder land uses by itself are an important determinant of fire. Actually, the presence of plantations is not a significant factor for fire. Although tree crops may be prone to fire (Saharjo and Watanabe, 2000) or be the focus of social conflicts between small- and large-holders, this is not reflected in the statistical results. Similarly, small-holder land uses are not related to fire occurrence. Apparently these areas are neither especially prone to fire nor fully protected against fire. Fires that would be associated to slash-and-burn cultivation are not identified inside the small-holder area. However, distance to small-holder areas is a significant variable that increases the odds of fire two times. This indicates that small-holders are more likely to clear close to the area they currently occupy, often for agricultural expansion. By contrast, the distance to large-holder plantations was not a significant variable in determining fire probability. This suggests that plantations are not expanding in the vicinity of their current area.

Elevation is a significant explanatory variable. The lower areas (0–100 m) have a 3.5 times higher fire odds than the higher elevations. This maybe related to the low accessibility of the hills and mountains in Jambi. The high altitude areas are also less attractive to small- and large-holders since rubber, mango and oil-palm trees do not grow very well at these altitudes. Finally, a large area of the mountain forest of Jambi is a national park.

There are two large rainfall zones in the area: a medium wet zone (rainfall 2500–3000 mm a year) and a dry zone (rainfall 1800–2200 mm a year). The drier zone increases the odds of fires 2.2 times. This suggests that a low fuel moisture is a predisposing factor for fires. The presence of logged-over forests is not a significant variable in the fire model. This differs from findings in the Amazon, where the return interval of fires was higher in logged-over forests affected by selective logging (Nepstad et al., 2001). Further, land suitability for rubber tree crop is a significant variable and increases the odds of fire more than five times. This may reveal an expansion of agriculture accompanied by forest clearing in areas suitable for rubber. Rubber is cultivated both by large- and small-holders. The oil-palm suitability was not a significant variable in 1992/1993, but this may have changed today.

In general, accessibility variables such as distance to towns, rivers or roads are not significant in explaining fire occurrence at the level of the province. However, a zone 15–20 km from towns shows an increase of fire odds 2.5 times compared to areas further than 20 km from towns. It is likely that areas close to towns are well settled and intensively used, and will not experience any new clearing. Apparently, the frontier where there is still room for new clearing is now 15–20 km from towns. This also suggests that land clearing using fires is not taking place any more along roads or rivers, and that accidental fires along transportation axes are not frequent.

A second model was tested with the same variables but only on forest land covers (natural forest and logged-over forest, including all land uses that take place in forest areas), to address the question of the vulnerability of forests to fire. The results show (Table 6) that the model fit is good with $\rho^2 = 0.26$ and that presence of transmigration projects, dry climate and absence of logging concessions are also strong determinants of fires in forests. However, in this model, accessibility is much more important as a spatial determinant of fires. Distance to roads and distance to towns are both significant variables. Close to roads (1–5 km), the odds of fire increases almost five times compared to areas far (>20 km) from roads. Thus, the higher accessibility increases the odds of fire for forests. This is unlikely to be caused by accidents since forests are not prone to fires. More likely is that these forested areas are more attractive for expansion especially along roads. This is not the case in the model covering the entire province since, along existing roads, there are well-established farms that decrease the chance of fire. Also distance to towns at 5–10 km increases the odds of fire more than five times in forested areas.

A third model was used to assess fires in non-forest areas (small-holder land and secondary vegetation). The model showed a fair fit ($\rho^2 = 0.18$) and similar results as for the model over the entire province, with

Table 6
Significant parameters ($P < 0.05$) of the logistic regression for forest areas in Jambi Province, with odds ratio and the reference category of the odds ratio ($\rho^2 = 0.26$ and Wald test $\beta \leq 0.0001$)

Significant variables		Estimate	Error	χ^2	$P > \chi^2$	Odds ratio	Compared to
	Intercept	−4.49	0.55	66.07	<0.0001		
Allocation	Logging concession	−0.30	0.16	3.63	0.05	0.55	Absence of logging concessions
	Allocated to production forest	0.61	0.28	4.96	0.026	2.34	Not allocated zone
	Allocated as transmigration area	1.77	0.54	10.59	0.0011	5.86	Absence of transmigration
Accessibility	Distance to roads, 1–5 km	0.77	0.27	4.96	0.026	4.88	Distance to roads, >20 km
	Distance to towns, 5–10 km	0.60	0.26	5.14	0.023	5.23	Distance to towns, >20 km
Predisposing	Eco-climate is dry (rainfall between 1800 and 2200 mm)	0.50	0.18	7.76	0.005	2.75	Eco-climate is medium wet (rainfall between 2500 and 3000 mm)

Table 7
Significant parameters ($P < 0.05$) of the logistic regression for non-forest areas in Jambi Province, with odds ratio and the reference category of the odds ratio ($\rho^2 = 0.18$ and Wald test $\beta \leq 0.0001$)

Significant variables		Estimate	Error	χ^2	$P > \chi^2$	Odds ratio	Compared to
	Intercept	−3.84	0.49	59.67	<0.0001		
Allocation	Presence of transmigration project	1.33	0.63	4.45	0.035	4.36	Absence of transmigration
Accessibility	Distance to towns, 10–15 km	−0.69	0.34	4.31	0.038	0.20	Distance to towns, >20 km
	Distance to towns, 15–20 km	0.74	0.37	4.05	0.044	0.85	Distance to towns, >20 km
Predisposing	Suitability rubber	1.25	0.52	5.76	0.016	7.99	Unsuitable for rubber
	Eco-climate is dry (rainfall between 1800 and 2200 mm)	0.50	0.22	4.77	0.029	2.72	Eco-climate is medium wet (rainfall between 2500 and 3000 mm)

significant influence of presence of transmigration projects, suitable areas for rubber and dry climate (Table 7). Thus, in these areas, accessibility does not determine the location of fire.

7. Discussion

The conceptual model of fire occurrence can now be further evaluated on the basis of the results from this statistical model. Predisposing conditions such as dry climate, soil suitability for the main tree crops and low elevation are important variables in determining the probability of fire occurrence. However, these variables only explain the potential for fires while fire occurrence in relation to proxy variables for sources of ignition describe the actual fire probability.

The main proximate causes of fires are land allocation, presence of transmigration projects, absence of logging companies, suitability for rubber and proximity to small-holder areas. Note that the location of transmigration projects and logging concessions are also determined by land allocation policies. The importance of land allocation shows that national policies are important in controlling fire occurrence. Policy decisions on which areas are allocated to transmigration projects or for conversion to plantations or production are the main driving forces of fires. The increase in fire in areas with transmigration projects is logical because of the clearing that is required for the establishment of the project. Although the allocation to production forest increases fire probability, the presence of actual logging concessions decreases fire probability. Fire probability thus

increases in areas allocated for logging when these areas are not yet under use or are abandoned by the companies. Likely the attractiveness of these areas for conversion by large- or small-holders is high given their accessibility.

The fact that soil suitability for rubber is also a major driving force for fire occurrence suggests that these areas are rapidly converted, probably by both large- and small-holders. The presence of plantations does not seem to increase fire vulnerability and plantations do not expand in areas close to their immediate surroundings using fires. By contrast, several fires are found around small-holder areas, suggesting an expansion of small-holder agriculture.

There is no direct statistical evidence from this coarse resolution analysis that social conflicts drive fires. Assessing the role of social conflict would require finer scale data, probably at the household or community levels. Proximity to rivers, roads and towns are not significant explanatory variables overall for the province but are significant for fire location in forest areas only, which represent 30% of the total area and 50% of the fires. Accessibility increase possible accidental ignition of fires (which is unlikely in forest) and provides more incentives for forest clearing for agricultural expansion. In summary, among the factors analysed here, those that are related to fire occurrence in Jambi Province are national policies (by allocating areas to new land uses), large-holders and small-holders (close to their fields for the latter, in suitable areas for their main crops, and close to roads and towns in forest areas).

Note that the physical aspects of the landscape related to fuel load and flammability were not included explicitly in this analysis. However, land cover, as a proxy for biomass and thus for fuel load, was not a significant explanatory variable of fire. By contrast, climate, as a proxy for fuel moisture, was related to fire occurrence. The study thus mostly uncovers determinants of fires associated with land use. It is possible that local variations in species composition, stand age and density, local microclimate and soil conditions would determine fine scale differences in fuel condition and flammability, and thus in fire pattern. However, given that our model controls for broad scale variations in these factors via the land cover, soil suitability and landform variables, fuel variables are only likely to cause fine-grained differences in burning patterns and thus are unlikely to affect our results on province-wide spatial determinants of fires.

Finally, the results are limited in time to the 1992/1993 burning season. These years were chosen given the availability of a good quality land use/cover map. Since then, the agricultural setting in Indonesia has changed. A large boom in the agro-industrial crops, mainly oil-palm, has taken place. However, rubber remains the main cash crop for small-holders. Further, an extreme drought in 1997/1998 triggered a large vegetation fire episode. The determinants of fire found in this research might therefore differ from those of 1997/1998 and of today. In particular, the relative responsibility of small- and large-holders in causing fires may have changed following changes in the agricultural economy of the region. However, some of the processes uncovered in this study are likely to continue to influence fire patterns as well.

8. Conclusion

The objective of this study was to understand the major spatial determinants of fires for the 1992/1993 burning season. From this understanding, the goal was to generate insights on the place where fires take place, the actors involved and the driving forces. It is clear that fires occur in many land use and land cover types. The results show that fire occurrence in Jambi Province in 1992/1993 was determined both by predisposing conditions (mostly climate, elevation and suitability for specific tree crops) and human-related causes (presence of transmigration projects and land allocation to specific land uses). National policies are thus a major driving forces of fires through land allocation. Few fires seem to be accidental. While logging companies control fire during their exploitation of concessions, logged-over forests and forests allocated to production but not yet under use have many fires. In 1992/1993, large- and small-holders were likely to be both responsible for fire occurrence, even though the data do not allow to estimate the proportion of fires that can be attributed to these different categories of land managers.

Most fires can be attributed to land allocation policies and land use rather than to natural ignition sources and land cover factors that would control fire propagation via fuel availability and flammability. The

high cost to ecosystems and societies related to fires in Indonesia must therefore be controlled by appropriate land use policies.

Acknowledgements

This study was started and supported by the International Centre for Research in Agroforestry (ICRAF) within the context of the *Alternative to Slash-and-Burn* programme, the United Nations Educational and Cultural Organisation (UNESCO) and the Centre for International Forestry Research (CIFOR), Bogor. It was further helped by co-operation with United States Forest Service, Remote Sensing Facilities (USFS-RSAC), Salt Lake City. The authors like to thank BIOTROP, Dr. Upik Wasrin for her contribution. The work was supported in part by the World Bank's project on the social and environmental consequences of growth-oriented policies and the Asian Development Bank. The responsibility is of the authors alone.

References

Allen, T.G., 1986. Land clearing in African savannas. In: Lal, R., Sanchez, P.A., Cummings, R.W. (Eds.), Land Clearing and Development in the Tropics. Balkema, Rotterdam, pp. 69–80.

Ataga, D.O., Onwubuya, I.L., Omoti, U., 1986. In: Lal, R., Sanchez, P.A., Cummings, R.W. (Eds.), Land Clearing and Development in the Tropics. Balkema, Rotterdam, pp. 87–96.

Barber, C.V., Schweithelm, J., 2000. Trial by fire, forest fire and forest policy in Indonesia's era of crisis and reform. World Resource Institute, Washington, DC.

Bompard, J.M., Guizol, P., 1999. Land management in the province of South Sumatra, Indonesia. Fanning the flames: the institutional causes of vegetation fires. European Union Forest Fire Prevention and Control Project, Palembang.

Bowen, M.R., Bompar, J.M., Anderson, I.P., Guizol, P., Gouyon, A., 1999. Anthropogenic fires in Indonesia: a view from Sumatra. European Union Forest Fire Prevention and Control Project, Palembang.

BPS (Badan Pusat Statistik), 1992. Statistical Yearbook of Indonesia 1991. BPS, Jakarta.

Chomitz, K.M., Gray, D.A., 1996. Roads, land, markets and deforestation: a spatial model of land use in Belize. Report from the Environment, Infrastructure, and Agricultural Division, Policy Research Department, World Bank Economic Review.

Cochrane, M.A., Alencar, A., Schulze, M.D., Souza Jr., C.M., Nepstad, D., Lefebvre, P., Davidson, E.A., 1999. Positive feedbacks in the fire dynamics of closed canopy tropical forests. Science 284, 1832–1835.

Crutzen, P.J., Goldammer, J.G., 1993. Fire in the Environment—The Ecological, Atmospheric and Climate Impact of Vegetation Fires. Wiley, Chichester, UK.

Ehrlich, D., Lambin, E., Malingreau, J.-P., 1997. Biomass burning and broad-scale land cover changes in western Africa. Remote Sens. Environ. 61, 201–209.

ESA, 1997. World Fire Atlas on CD, Fire Ionia Tool. ESA/ESRIN, Frascati, Italy.

ESRI, 1993. Digital Chart of the World. ESRI, Redlands, CA.

Eva, H., Lambin, E.F., 1998. Remote sensing of biomass burning in tropical regions: sampling issues and multisensor approach. Remote Sens. Environ. 64, 292–315.

Eva, H., Lambin, E.F., 2000. Fires and land cover change in the tropics: a remote sensing analysis at the landscape scale. J. Biogeogr. 27, 765–776.

Fearnside, P.M., 1983. Land use trends in Brazilian amazon region as factors in accelerating deforestation. Environ. Conserv. 10, 141–148.

Flasse, S.P., Caccato, P., 1996. A contextual algorithm for AVHRR fire detection. Int. J. Remote Sens. 17, 419–424.

Fujisaka, S., Bell, W., Thomas, N., Hurtado, L., Crawford, E., 1996. Slash-and-burn agriculture, conversion to pasture and deforestation in two Brazilian colonies. Agric. Ecosyst. Environ. 59, 115–130.

Giri, C., Shrestha, S., 2000. Forest fire mapping in Huay Kha Khaeng wildlife sanctuary, Thailand. Int. J. Remote Sens. 21, 2023–2030.

Goldammer, J.G., 1999. Forest on fire. Science 284, 1782–1783.

Goldammer, J.G., Siebert, B., 1990. The impact of droughts and forest fires on tropical lowland rain forest of east Kalimantan. In: Goldammer, J.G. (Ed.), Fire in the Tropical Biota. Ecosystem Processes and Global Challenges, pp. 11–31.

Gouyon, A., 1999. The sustainable development of tree crops and the prevention of vegetation fires in South Sumatra, Indonesia. Jungle Rubber. European Union Forest Fire Prevention and Control Project, Palembang.

Holdsworth, A.R., Uhl, C., 1997. Fire in Amazonian selectively logged rain forest and the potential for fire reduction. Ecol. Appl. 7, 713–725.

Hosmer, D.W., Lemeshow, S., 1989. Applied Regression Analysis. Wiley, New York.

Huckabay, J.D., 1989. Man and the disappearance of the Zambezian dry evergreen forest. In: Kadomura, H. (Ed.), Savannization Processes in Tropical Africa. Zambia Geographical Association, Lusaka, pp. 89–106.

IC-SEA, 1999. Land-use change and terrestrial carbon stocks: capacity building, impacts assessment, and policy support in south and southeast Asia (APN 99004). Final Activity Report IC-SEA.

Jannick, M.S., Beckett, D.R., 1987. A logit analysis of private woodlot owner's harvesting decisions in New Brunswick. Can. J. For. Res. 18, 330–336.

Kleinbaum, D.G., Lawrence, L.K., Muller, K.E., Nizam, A., 1998. Applied Regression Analysis and Other Multivariable Methods. Duxbury Press, Pacific Grove, USA.

Laumonier, Y., 1997. The Vegetation and Physiography of Sumatra. Kluwer Academic Publishers, Amsterdam.

Ludeke, A.K., Maggio, R.C., Reid, L.M., 1990. An analysis of anthropogenic deforestation using logistic regression and GIS. J. Environ. Manage. 31, 247–259.

Malingreau, J.P., Stephens, G., Fellows, G.L., 1985. Remote sensing of forest fires: Kalimantan and North Borneo in 1982–1983. Ambio 14, 314–321.

Menard, S., 1995. Applied Logistic Regression Analysis. Quantitative Applications in the Social Sciences, vol. 106. Sage, London.

Mertens, B., Lambin, E.F., 2000. Land-cover trajectories in southern Cameroon. Ann. Assoc. Am. Geogr. 90 (3), 467–494.

MOFEC, 1993. National Masterplan for Forest Plantations. MOFEC, Jakarta.

Nepstad, D.C., Klink, C.A., Uhl, C., Vieira, I.C., Lefebvre, P.A., Pedlowski, M., Matricardi, E., Negreiros, G., Browen, I.F., Amaral, E., Homa, A., Walker, R., 1997. Land use in Amazonia and the cerrado of Brazil. Ciencia Cult. 49, 73–86.

Nepstad, D.C., Verissimo, A., Alencar, A., Nobre, C., Lima, E., Lefebvre, P., Schlessinger, P., Potter, C., Moutinho, P., Mendoza, E., Cochrane, M., Brooks, V., 1999. Large scale impoverishment of Amazonian forests by logging and fire. Nature 398, 505–508.

Nepstad, D., Carvalho, G., Barros, A.C., Alencar, A., Capobianco, J.P., Bishop, J., Moutinho, P., Lefebvre, P., Silva Jr., U.L., 2001. Road paving, fire regime feedbacks, and the future of Amazon forests. For. Ecol. Manage. 5524, 1–13.

Phillips, J., 1974. Effects of fire in forest and savanna ecosystems of sub-Saharan Africa. In: Kozlowski, T.T., Ahlgren, C.E. (Eds.), Fire in Ecosystems. Academic Press, New York, pp. 435–481.

Prakash, A., Gupta, R.P., 1999. Surface fires in Jharia coalfield, India—their distribution and estimation of area and temperature from TM data. Int. J. Remote Sens. 20 (10), 1935–1946.

RePPProT, 1988. Regional Physical Planning Programme for Transmigration. Land Resource Department/Bina Program. Review of Phase I Results, Sumatra. Land Resources Department, Overseas Development, Natural Resources Institute, Overseas Development Administration, London, UK; and Direktorat Bina Program, Direktorat Jenderal Penyiapan Pemukian, Departemen Transmigrasi, Jakarta.

Saharjo, B.H., Watanabe, H., 2000. Estimation of litter fall and seed production of *Acacia mangium* in a forest plantation in South Sumatra, Indonesia. For. Ecol. Manage. 130 (1–3), 265–268.

SAS, 1997. SAS/STAT Software: Changes and Enhancements through Release 6.12. SAS Institute, Inc., Cary, NC.

Schuster, E.G., 1983. Evaluating nonindustrial private land owners for forestry assistance programs: a logistic regression approach. Research Paper INT-320. United States Department of Agriculture, Forest Service Intermountain Forest and Range Experiment Station.

Schweithelm, J., Jessup, T., Glover, D., 1999. Conclusions and policy recommendations. In: Glover, D., Jessup, T. (Eds.), Indonesia's Fires and Haze: The Costs of a Catastrophy. Institute of Southeast Asian Studies, Singapore, pp. 130–145.

Siegert, F., Hoffmann, A.A., 2000. The 1998 forest fires in East Kalimantan (Indonesia): a quantitative evaluation using high resolution, multitemporal ERS-2 SAR images and NOAA-AVHRR hotspot data. Remote Sens. Environ. 72, 64–77.

Stolle, F., Tomich, T.P., 1999. The 1997–1998 fire event in Indonesia. Nat. Resour. 5 (3), 22–30.

Swaine, M.D., 1992. Characteristics of dry forest in West Africa and the influence of fire. J. Veg. Sci. 3, 363–364.

Vega Garcia, V., Woodward, P.M., Titus, S.J., Adamowicsz, W.L., Lee, B.S., 1995. A logit model for predicting daily fire occurrence of human caused forest fires. Int. J. Wildl. Fires 5 (2), 101–111.

von Thünen, J.H., 1826. Der Isolierte Staat in Beziehung der Landwirtschaft und Nationalökonomie. In: Peter Hall (Ed.), Isolated State von Thünen. Pergamon Press, Oxford.

Walsh, S.J., Evans, T.P., Welsh, W.F., Entwise, B., Rindfuss, R.R., 1999. Scale-dependent relationships between population and environment in northeastern Thailand. Photogrammetric Eng. Remote Sens. 65, 97–105.

Whitten, T., Damanik, S.J., Anwar, J., Hisyam, N., 2000. The Ecology of Sumatra. Periplus Editions (HK) Ltd., Jakarta.

Wrigley, N., 1985. Categorical Data Analysis for Geographers and Environmental Scientists. Longman, New York.