Environmental Conservation **30** (4): 375–387 © 2003 Foundation for Environmental Conservation DOI:10.1017/S0376892903000390

Interprovincial and interannual differences in the causes of land-use fires in Sumatra, Indonesia

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Date submitted: 26 July 2002 Date accepted: 18 June 2003

SUMMARY

Despite the vast destruction caused by recent fires in Sumatra's forested areas, there have been few analyses of their spatial variability and causes. Various combinations of predisposing and land-use factors in space and time may cause fires. For each variable, fire densities were calculated to assess the spatial and temporal association between natural and cultural landscape variables and fire occurrence in four provinces in Sumatra, Indonesia for a non-dry year (1999) and a dry year (1997). This was complemented by a single multivariate logistic regression for the two years over the four provinces with fires as the dependent variable and land use and predisposing factors as independent variables. The provincial analyses showed that fires are determined by multiple, interacting factors and that these factor interactions are not the same in all provinces. In the non-dry year, the factors were only weak determinants of fires and only few determinants were common to all provinces (presence of undisturbed forests, elevation, smallholder area, land allocation to production area). In the dry year, more determinants of fires were found to be common to all provinces (presence of undisturbed forests, elevation, land allocation to production or conversion areas, presence of plantations, distance from roads). This led to the identification of pathways that increased fire probability. The first step was the allocation of land to different land-use types and stakeholders by national policies. If allocated to large-scale landowners, fires were more likely to occur in plantations, especially in the dry year. Logging concessions did not play a major role in increasing the incidence of fire. However the strongest increase in fire probability was outside the areas under use, in undisturbed forests. We conclude that areas not yet used by large-scale landowners were more prone to fire, indicating a serious threat to the remaining forests in this region.

Keywords: fire, land use, biomass burning, forest, deforestation, Indonesia, Sumatra

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INTRODUCTION

Fires have always been part of Indonesia's wet tropical forest ecosystem (Goldammer & Seibert 1990) and are a common tool for land clearance (Schweithelm 1998; Tomich *et al.* 1998; Ketterings *et al.* 1999). Recently however, the dramatic fire episode of 1997/1998 associated with the El Niño climatological phenomenon had large effects on the environment and on Indonesian society (Dennis 1999; Glover & Jessup 1999; Goldammer 1999; Schweithelm *et al.* 1999; Siegert & Hoffmann 2000). The destruction wrought by these fires was attributed to a combination of increased land vulnerability to fire because of land-use changes by large-scale landowners, a severe drought, institutional failure to prevent and control fires (Schweithelm 1998; Applegate *et al.* 2001; Jepson *et al.* 2001; Siegert *et al.* 2001) and natural susceptibility of logged-over forests to fire (as found in East-Kalimantan by Siegert *et al.* 2001). There are large differences between the provinces across the Indonesian archipelago in terms of land use and biophysical factors. Fire occurrence and impact thus vary between different provinces and different years (Stolle 2000*a*).

Fire is determined by predisposing conditions, that define the 'natural' vulnerability to fire, and anthropogenic factors, that cause the spark (Malingreau *et al.* 1985; Barber & Schweithelm 2000; Giri & Shrestha 2000; Stolle *et al.* 2003). The factors necessary for fires to occur are presence of flammable fuel and an ignition source (Fig. 1), the former depending on climatic, soil and vegetation conditions, and previous fire events, and the latter natural (for example lightning) or anthropogenic. If the ignition source is anthropogenic, it can be caused deliberately (as part of land management), or accidently through negligence. Land use and biophysical factors such as the presence and distribution of plantations (Bowen *et al.* 2000), logged-over forests (Siegert *et al.* 2001), surface moisture and accessibility determine the landscape distribution of fires. Land-use intensity and farming systems also determine the level of fire suppression measures. Land-use change also controls fire occurrence (Fujisaka *et al.* 1996; Ehrlich *et al.* 1997; Eva & Lambin 2000). In particular, the opportunity for large-scale landowners to clear large tracks of land is seen as one of the main factors causing fires in dry years in Indonesia (Schweithelm 1998; Siegert & Hoffmann 2000; Jepson *et al.* 2001). In Indonesia, the spatial pattern of land-use change is largely determined by policies that set land conversion targets for plantations (Wakker 1998) and plan transmigrant settlement schemes (Holden & Hvoslef 1995).

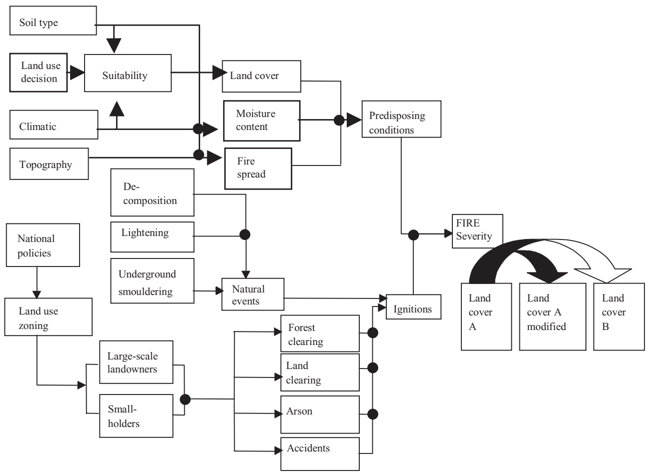

Figure 1 Conceptual model of fire occurrence. The upper part of the figure represents the predisposing conditions for fire. The lower part shows the pathways for ignition of fires in four levels: proximate causes, human actions and natural events, land-use zoning, and national policies.

Below, we present our research hypotheses and their rationale, firstly for predisposing factors for fires and secondly for the impact of land use on fires.

Predisposing factors

In dense humid forest environments, a dry year is likely to be associated with more fires because of the increased flammability of the available fuel. In previous studies in Indonesia, based on monthly rainfall data, no relationship between diminished vegetation vigour because of drought and fire was found (Illera *et al*. 1996; Stolle 2000*b*). In fact, it takes a few weeks to months without rain, depending on the cover type, to dry out forests sufficiently to increase fire probability (Goldammer & Seibert 1990; Uhl & Kauffman 1990; Couturier *et al*. 2001). However, a significant negative correlation between annual average rainfall and total fire occurrence over a year is expected, given the cumulative effect of drought on fire risk over an entire season.

Landform is another predisposing factor for fires. Swamps are fire resistant in wet years since they are waterlogged. In dry years, however, the water table goes down and the fire-prone organic peat layer burns easily. With the recent boom in tree-crop plantations that are able to grow in swamps, such as oil-palm (Badan Pusat Statistik 1999; Mutert *et al*. 1999), large-scale landowners have started to clear swamps, especially in dry years. Smallholders also use swamps intensively in dry years for *sonor* rice cultivation (Suyanto *et al*. 2000). The swamps are thus expected to have few fires in non-dry years, but to concentrate fires in dry years.

Low altitudes are associated with swamp areas (Table 1).

Table 1 Selected characteristics of the four provinces analysed in Sumatra. Sources: Iremonger *et al*. (1997), Ministry of Forestry and Estate Crops, and Ministry of Transmigration.

Factor	*Provinces*			
	Riau	*Sumatera Selatan*	*Jambi*	*Lampung*
Per cent provincial area under lowland forest cover	19	11	36	14
Area (in km^2) granted as logging concessions and per cent of provincial area under logging concessions	46446 58.17	16564 17.76	21445 58.50	171 0.52
Area (in km^2) granted plantation and per cent of provincial area under plantation	8961 10.20	3936 0.33	2664 5.48	221 0.67
Per cent of provincial area with an elevation < 50 m that are swamps	88	97	86	88
Per cent of transmigration areas in swamps	54	43	53	12
Per cent of provincial area in relation to distance from roads				
0-5 km	30	26	50	57
>20 km	28	17	9	4
Per cent of swamp area in relation to distance from roads				
0–5 km	11	8	10	26
5–10 km	14	13	15	32
10–15 km	13	11	19	23
15–20 km	12	7	13	5
>20 km	50	60	43	13
Per cent of provincial area granted as logging concession by date				
<1980	46	13	34	0
1980–1985	2	1	4	0
1985–1992	10	4	20	0
Per cent of provincial area granted as tree-crop plantation by date				
<1990	6.7	0.2	0.2	0.0
90–92	3.8	0.0	8.2	0.0
92–97	3.1	0.2	12.3	0.6
>1997	22.5	3.1	7.9	2.3

Medium altitudes (50–100 m) correspond to the plains where most settlements and economic activities are concentrated, since they have the most suitable soils for the main crops. Fire as a land management and forest conversion tool is thus expected to be frequent in the plains. The higher rainfall in hills and mountains (Regional Physical Planning Programme for Transmigration 1988), their steep slopes, and their low suitability for rubber and oil palm make these areas less attractive for large-scale clearing (Holmes 2000). In normal years, high altitudes are thus expected to have few fires, while the medium altitudes with their favourable conditions for large-scale crops are expected to have the highest fire densities.

Land cover is also a predisposing factor for fires. Equatorial rainforest is, in its undisturbed form, generally resistant to fires (Goldammer 1991). However few forests in the study area are undisturbed as they have been altered by logging, conversion to plantations and intrusion of smallholders (FAO [Food and Agricultural Organization of the United Nations] 1990; Holmes 2000). Half of the standing forests in Sumatra were under logging concessions in 1997 (Holmes 2000). Undisturbed forests are thus expected to have a lower fire density than non-forested areas and forests under use.

Land-use factors

Ignition of fires is mostly associated with land use, which is partly determined by land tenure. Most land managers in Indonesia use fire to clear forests. Smallholder land use consists of mixed forest gardens with upland and lowland rice fields. Large-scale landowner land uses are mainly monoculture plantations or logging concessions. Areas occupied by smallholders are generally more intensively managed and thus better protected against accidental fire than areas used by large-scale landowners (Wiersum 1997). Smallholders are also less likely to clear on a large scale, in contrast to large-scale landowners. Fires are thus expected to be less frequent in smallholder than in large-scale landowner areas, especially in dry years.

Different large-scale landowner land uses, such as plantations and logging concessions, have a varying vulnerability to fires. In large resettlement schemes, although transmigrants are smallholders, the land is initially managed as one large estate and large-scale landowners clear the forest. Such schemes are therefore discussed here as a large-scale landowner land use. A different level of fire use is expected at each of the development stages of large-scale landowner land uses, such as opening, exploitation and abandonment of the concession.

Plantation concessions start with land clearing, which is almost exclusively done by burning the area (Sargeant 2001). This may be the main source of fire in Indonesia (Schweithelm 1998; Potter & Lee 1999; Sargeant 2001). Agricultural exploitation initially increases the risk of fires, especially in dry years, since young crops are more vulnerable to fires (Gouyon 1999). Once the crops have reached maturity, fewer fires are expected. But, since costly fire-preventative measures are not always implemented (Vayda 1999), they may still be relatively fire-prone in dry years (Couturier *et al*. 2001). Social conflicts over land rights also cause fire in plantation areas (Tomich *et al*. 1998). Abandonment of plantations is rare.

The opening of a transmigration site also starts with forest clearance by fire. However, once smallholders are resettled, land is more intensively managed and thus better protected against fire. However, transmigration sites may be abandoned after several years (Holden & Hvoslef 1995), leaving unmanaged fire-prone vegetation, especially in swampy areas where many transmigrant projects are established (Table 1).

Logging concessions have a low vulnerability to fire in the initial and exploitation stages. However, fire risk increases significantly in the open secondary forest left after logging activities have ceased (Uhl & Kauffman 1990; Siegert *et al*. 2001). The older abandoned areas, which have recovered from the logging disturbance, are less fire-prone (van Nieuwstadt *et al*. 2001), but illegal logging (Jepson *et al*. 2001), by smallholders and large-scale landowners alike, maintains a high fire risk.

In summary, fire occurrence in large-scale landowner land uses depends on the type and stage of land use. Plantations (tree crops and timber trees) are expected to have the highest fire risk, especially in the initial stage of occupation. Transmigration areas are also expected to have a high fire risk in the initial stage but a low fire risk in the exploitation stage. Logging is expected to have a lower risk of fire, but the risk increases after abandonment of the concessions.

Accessibility increases the chance of fire owing to the increased opportunities for accidental fires and clearing (Nepstad *et al*. 2001), unless there is already a long history of occupation. Accidental fires along roads are only expected in dry years. In non-dry years, fires are less likely along roads.

Land allocation through national policies is a major underlying cause of fires (Stolle *et al*. 2003). A few fires are expected in areas allocated to protected zones and national parks, except in dry years when accidental fires are frequent. Higher fire occurrence is expected in both dry and non-dry years in areas allocated to production forests, where only selective logging is allowed, and even more so in conversion forests, where clear-cutting and conversion to plantations are allowed. Forests allocated to these zones and not yet under active management by specific concession holders are very vulnerable to illegal use by smallholders and large-scale landowners, especially in dry years.

The main hypothesis was that elevated fire risk is a product of land use, biophysical conditions and opportunities created by land-use policies and accessibility. A more specific objective was to identify general pathways leading to fire that could be used by planners to design a policy framework to decrease the risk of fire.

METHODS AND STUDY AREA

We determined the potential probability of occurrence of forest fires. For each variable, fire densities were calculated to measure spatial and temporal associations between a given variable and fire occurrence per province and per year. Observed associations were compared with the expected associations outlined in the previous section. Physical, socio-economic and political characteristics of provinces were used to explain unexpected fire patterns. Finally, an overall multivariate model of fire occurrence in the four provinces, in two years with contrasting climatic conditions, was developed to evaluate the relative power of these factors to explain fires within the entire study area.

Study area

This study investigated four provinces on the island of Sumatra, namely, from south to north: Lampung, Sumatera Selatan (South Sumatra), Jambi and Riau (Fig. 2). Sumatra Island has a mountain range running from north to south. West from this mountain range is a small coastal strip while, in the east, a plain gently slopes down to the coast forming large swamp areas in the coastal zone. The rainfall is slightly higher in the northern provinces (Table 2). The study area has a diversity of actors (smallholders and large-scale landowners, new settlers and long settled farmers), and land-use and land-cover types (for example primary forests, plantations, and secondary forests) (Table 1). After the introduction of the rubber tree, *Hevea brasiliensis*, at the start of the 20th century, rubber became the main crop for large-scale landowners and smallholders. Smallholders cultivated the rubber trees in gardens (a type of secondary forest with a high percentage of rubber trees) while large-scale landowners established rubber plantations. In the 1970s, large-scale logging commenced, and has become what is now one of the commonest land uses on Sumatra. Large-scale transmigration also took place from Java and Bali to Sumatra, while, in the late 1980s, pulp and timber plantations appeared. In the mid-1990s, land conversion to large-scale oil-palm plantations was implemented.

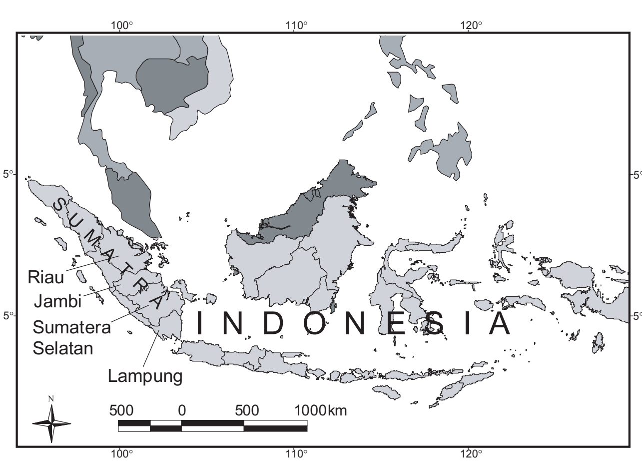

Figure 2 Location of the study area in South-east Asia.

Table 2 Monthly and annual rainfall for four provinces in Sumatra. Sources: Deutsche WetterDienst Global Precipitation Climatology Centre and Regional Physical Planning Programme for Transmigration.

Factor	*Provinces*			
	Riau	*Sumatera Selatan*	*Jambi*	*Lampung*
Average monthly rainfall (mm month^{-1})				
1992	215	190	218	167
1993	246	230	248	197
1997	161	141	140	121
1998	254	269	258	234
1999	226	218	232	200
30 year average rainfall (mm month^{-1})				
	212	236	222	202

Among the four provinces studied, Lampung has the longest history of settlement, industrialization and transmigration, and the associated forest conversion had already begun by the end of the 19th century (Imbernon 1999). This province has the highest population density in Sumatra and a good accessibility (Table 1). Not much land is left unoccupied and, recently, only minor land-use changes carried out by large-scale landowners have taken place. The forest cover is the lowest of the four provinces studied and is concentrated in one national park.

Sumatera Selatan has large-scale rubber plantations that started in the 1980s. The other large-scale landowner land uses are mainly old logging concessions (Table 1). The province has large swamps in the eastern part, many of them being already converted to agricultural or forestry uses. This province is well settled, except for the extensive swampy habitat. Large-scale landowner land uses do not occupy a major part of the province.

Jambi Province has recently been subject to a large increase in both logging activities and conversion to tree-crop plantations, but a large part of the province is still under old logging concessions (Table 1). The province has swamps in the eastern part, half of which being already converted to plantations and logging concessions. This province has few unoccupied areas, except for the swamps where land-use changes have recently been taking place. Large-scale landowners are heavily involved in logging concessions and tree-crop plantations.

Riau Province has also undergone large land-use changes even more recently (Table 1). Large forest areas still exist outside national parks and logging is still an important activity. The province has large swamps in the eastern part, which are not yet converted to plantations and logging areas. More than 10% of the province is under tree crop plantation, 50% of which were established after 1997 (Table 1). This province still has large forests, and large-scale landowners have recently undertaken significant land-use changes, with conversion to tree-crop plantations commencing around 1997.

Data selection

Data on active daily fires in Sumatra were obtained from several datasets, namely for 1992 from the Centre National de Recherches Météorologiques (http://www.cnrm.meteo.fr:8000/), for 1993 from the European Space Agency (ESA 1997), and for 1997–1999 from both the Japanese International Cooperation Agency (JICA) Forest Fire Prevention Management Project (http://ss.ffpri.affrc.go.jp/labs/fmrt/sawada/fire/) and the European Union Forest Fire Prevention and Control Project (http://www.mdp.co.id/ffpcp/). These fire data were derived by remote sensing from the National Oceanic Atmospheric Administration's Advanced Very High Resolution Radiometer sensors (NOAA-AVHRR). These sensors have thermal and near-infrared bands that were used to detect fires using a contextual detection algorithm (Flasse & Ceccato 1996). As slightly different detection methods were used (for example, thresholds for daytime fire detection were set at 320 K for the ESA data and 315 K for the JICA data), these datasets could not be strictly compared (Li *et al.* 2001). Interannual comparisons were only performed with the JICA data from 1997, a dry year, and 1999, a year with average rainfall. The spatial resolution of the NOAA-AVHRR data was 1.1 km^2, however 50×50 m fires could be detected given their high temperature. Thus, both large and very small but high temperature fires were identified. The common geolocation error of the NOAA-AVHRR data in Indonesia was around 3 km (Siegert & Hoffmann 2000).

Data on several explanatory variables were collected:

- Distances from roads were divided into five categories (0–5 km, 5–10 km, 10–15 km, 15–20 km and more than 20 km); the tarmac roads were digitized from the Ministry of Transportation data.
- Presence of large-scale landowner land-uses in the form of plantations (timber and tree-crop) and logging concessions in long-established (plantations established before 1992 and logging concessions established before 1987) and recent (established after 1992 or 1987 for plantation and logging concessions respectively) categories. This last variable was a proxy for large-scale landowner land-use change.
- Presence of pre-1992 and more recent transmigration projects of the Ministry of Transmigration (source map from Ministry of Transmigration of Indonesia 1998).
- Land allocation in the so-called 'agreed forest use' categories for the areas governed by the Ministry of Forestry and Estate Crops (MOFEC) of Indonesia as decided in the 1980 *Tata Guna Hutan Kesepakatan* (TGHK). These categories being outside forestry zone, protection forest (including limited production), national park zone, production forest zone and conversion forest zone. In this analysis, only allocation zones not yet used by large-scale landowners were taken into account.
- Smallholder land uses, with areas not used by large-scale landowners close to (<5 km) roads used as a proxy in the absence of actual smallholder data. This is likely to have represented only a fraction of all smallholder areas. Areas further than 5 km from roads and not used by large-scale landowners were referred to here as non-large-scale landowner areas, and were a mix of natural and secondary forests, as well as smallholder land uses.
- Forest land-cover data were derived from 1988 data (Iremonger *et al.* 1997) on non-forest land and different forest types, which were updated for this study. Time series of data on the presence of large-scale landowner land uses were available from the Ministry of Forestry with updates for the expansion of large-scale landowners from 1992–1999. The known land-use changes were therefore used to update the land cover data. This resulted in three land-cover classes, namely non-forest, undisturbed forest and logged-over forest. Note that the land-use change data were only available for large-scale landowners. Land classified as being undisturbed land may thus have been used by smallholders.
- Mean annual precipitation data taken from the Deutsche WetterDienst Global Precipitation Climatology Centre (http://www.dwd.de/research/gpcc/visualizer/) categorized in five classes, namely lowest rainfall (0–100 mm $month^{-1}$), low rainfall (100–150 mm $month^{-1}$), medium rainfall (150–200 mm $month^{-1}$), high rainfall (200–250 mm $month^{-1}$) and highest rainfall (>250 mm $month^{-1}$).

Two further variables were derived from the above data: large-scale landowner land uses (plantations plus logging concessions plus transmigration sites) and land accessibility (proximity to a road and not allocated to a concession holder).

The land cover, land use and allocation data have several weaknesses (Regional Physical Planning Programme for Transmigration 1988; Dick 1991; Sunderlin 1999; Holmes 2000). The data were not always accurate and concessions could be cancelled, new concessions could be given out without being officially mapped, land cover could be changed and boundaries could be shifted. Further, illegal logging also contributed to land-use change (Jepson *et al.* 2001). Concerning the active fire maps, only a sample of all fires was detected, namely those that were taking place at the time of satellite overpass and under clear sky conditions (Eva & Lambin 1998). In particular, ground fires in logging concessions and undisturbed forests were unlikely to be detected as accurately as the other fires.

Data analysis

All datasets were gridded into 1 km^2 cells ($n = 261\ 681$ cells). The fire datasets were converted into a presence/absence variable per year and per cell. The spatial distribution of fires was then analysed by calculating fire for different land categories as:

Fire density (in % of area affected by fire) =

$$\left(\frac{\text{no. of fire pixels} \times 1\text{-km}^2 \text{ in a land class}}{\text{total area of that class}}\right) \times 100 \qquad (1)$$

Fire densities were used as a measure of association between fire occurrence and the land category under study in each province and year. High and low fire densities indicated strong positive or negative associations, while an average density indicated a weak association. These computations were not based on individual patches from a land class but for all patches from a land class for a given province, and for the dry or non-dry years (fire densities were compared between all transmigration areas in 1997 to all non-transmigration areas in 1997 for each province). Areas smaller then 1000 km^2 were ignored, as the geolocation inaccuracies were too high (indicated as 'na' for 'not available').

Spatial and temporal determinants of fire occurrence were also identified through multivariate logistic regression. Multivariate models represented the interactions between variables describing land attributes and estimated the power of these variables in 'explaining' the location of fires. The independent variables were the same as for the bivariate relationships tested. A 10% random sample of 1 km^2 cells was selected for the analysis, which resulted in 16 424 points including 458 fire points for the non-dry year (1999), and 16 423 points including 1245 fire points for the dry year (1997). The output of the model gave the relative increase in probability of fire with a certain landscape attribute that related to a proximate cause of fires. Only significant factors ($\alpha < 0.05$) were taken into account in this analysis. The strength of the factor in determining fire was quantitatively expressed in terms of an odds ratio, in other words a measure of the probability of fire in one class compared to the reference class. The pseudo-R^2 or p^2 was used to measure the model's fit. Values of p^2 between 0.2 and 0.4 should be considered as indicating a good model fit.

RESULTS

Relationship between fires and rainfall through time

Monthly fire data and monthly average rainfall data were weakly correlated, with or without a time lag factor. By contrast, the annual average rainfall data gave a much stronger correlation with fires in three of the four provinces (Table 3). The lowest correlation between annual fires and rainfall was found in Riau province, with an increase in fire density after 1997 even though rainfall was high that year (Table 2).

Fire density in swamp areas in non-dry and dry years

In Lampung and Jambi, there was a very large increase in fires in swamps during the dry year, however fire density only increased slightly in the swamps of Riau and Sumatera Selatan during the dry year. Drought was thus not the only factor in controlling biomass burning in swamp areas. In the two provinces where there was a strong increase in fire density in the dry year, swamps were relatively accessible (Table 1).

Table 3 Correlation between monthly and annual rainfall and fire numbers for four provinces in Sumatra. Sources: Deutsche WetterDienst Global Precipitation Climatology Centre and Regional Physical Planning Programme for Transmigration.

Factor	*Provinces*			
	Riau	*Sumatera Selatan*	*Jambi*	*Lampung*
Monthly rainfall versus monthly fire numbers				
1992	−0.40	−0.61	−0.52	−0.61
1993	−0.08	−0.46	−0.48	−0.55
1997	−0.35	−0.21	0.14	−0.53
1998	−0.40	−0.43	−0.65	−0.46
1999	−0.35	−0.64	−0.46	−0.66
Yearly rainfall versus yearly fire numbers				
	0.25	−0.78	−0.90	−0.77

Fire density at different altitudes

Fires in the non-dry year were concentrated in the medium altitude range, which was the area with most economic activities and settlements (Fig. 3). In the dry year, fires were concentrated in the medium and low altitude ranges, the latter corresponding to dried-out swamps (Fig. 3).

Fire density in undisturbed forests, forest areas and forest used for logging

The data could only corroborate the greater fire density in logged-over forests and the lower fire density in undisturbed

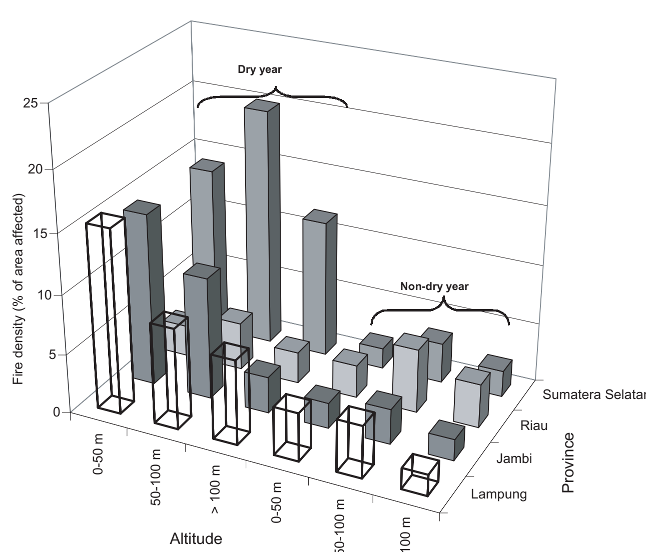

Figure 3 Fire density in relation to elevation in the dry and non-dry years for the four provinces.

forests compared to non-forest areas. Riau and Sumatera Selatan showed differences in fire density pattern.

Fire frequency in smallholder and large-scale landowner areas

The data confirmed the low fire occurrence in the areas assumed to be mainly occupied by smallholders, especially in the dry year (Fig. 4). By contrast, fire occurrence increased up to 10-fold in the dry compared to the non-dry year in large-scale landowner areas. Riau was an exception in this regard.

Fire occurrence in large-scale landowner land-uses of different types and stages

No data were available on abandonment of transmigration sites. Otherwise, the data indicated that fires depended on the land-use type, but only partly on the stage of occupation. Increases in fire density were found in newly established transmigration sites in Jambi and Sumatera Selatan and in newly established tree-crop plantation in Lampung, but also in the opening and exploitation stages for logging concessions in Sumatera Selatan (Fig. 5). As hypothesized, there was a lower fire density in older transmigration areas compared to older tree-crop plantations. However, high fire occurrence was generally found in long established large-scale landowner areas (Fig. 5). In Sumatera Selatan, exceptionally high fire densities were found in all land-use types, regardless of the age or type of large-scale landowner area. Especially high fire densities were found in logging concessions. Because no significant increase in fire density was found in logging concessions established before and after 1987, neither the natural susceptibility of logged-over forests to fire nor the attractiveness of logged-over forests to smallholders to convert these areas using fire could be confirmed for the four provinces under study.

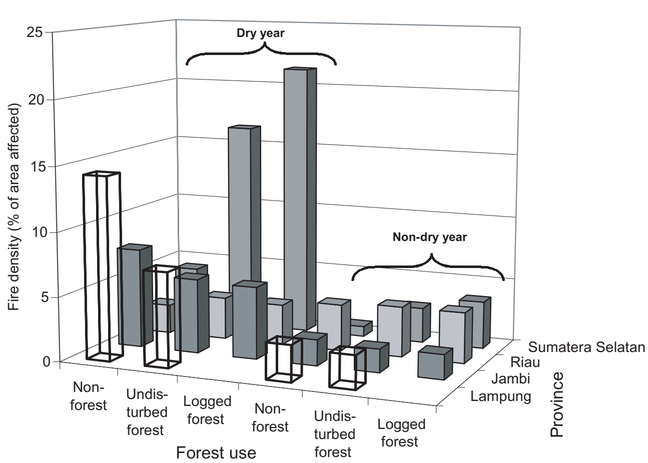

Figure 4 Fire density in the dry and non-dry years for the four provinces in relation to forest use.

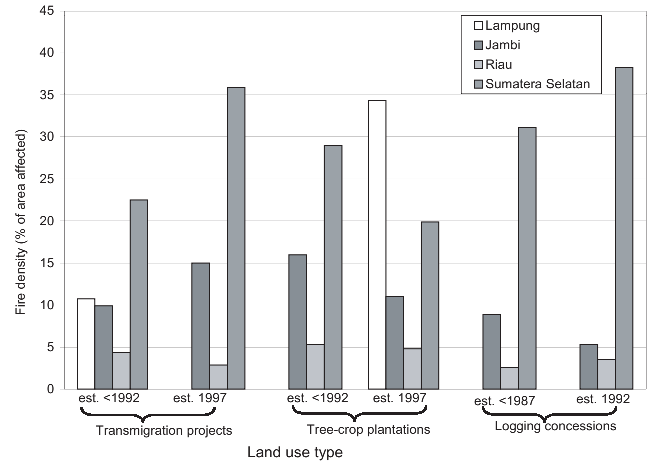

Figure 5 Fire density in large-scale landowner land use types in relation to age of the concessions in the dry year (1997) for the four provinces ('est.' = established).

Fire occurrence in highly accessible areas in the dry year

Only areas not yet used by large-scale landowners were used for this analysis. An increase in fire density was not found close to roads. The expected impact of accessibility on fires under dry climatic conditions was thus not confirmed for these four provinces.

Fires in areas allocated to production and conversion, but not yet officially used, in the dry year

This analysis also excluded areas already used by large-scale landowners. The areas allocated to production showed similar fire densities in the dry and non-dry years, while the conversion areas had only very high fire densities in the dry year (Fig. 6). Riau was an exception, with the highest fire

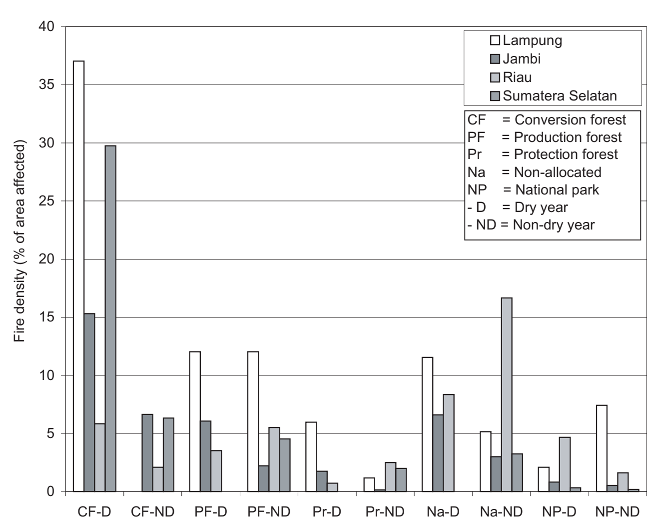

Figure 6 Fire density in different allocation zones in the dry (1997) and non-dry years (1999) for four provinces of Sumatra.

densities in non-allocated areas in the non-dry year. For the other three provinces, fire densities in the areas allocated to production and conversion were high. Since this analysis excluded areas mapped as being already used by large-scale landowners, forest use by large and/or smallholders was evidently taking place when there was the opportunity to clear land. Moreover, allocation to national park area was not a guarantee of low fire occurrence. In the non-dry year, non-allocated zones (i.e., in part, smallholder areas) had in general fewer fires than the production and conversion zones (except in Riau) but more than the protected areas and national parks.

Prediction of land-use fires

The bivariate analyses revealed that the spatial and temporal distributions of fires were related to several interacting factors. For an understanding of the determinants of fire occurrence in all four provinces, a single multivariate model of probability of fire occurrence, taking into account the interaction between factors, was derived for the dry and the non-dry years. It contained all explanatory landscape variables except for 'presence of national parks' and 'protected areas', which were strongly correlated with other factors and were thus causing multicolinearity. When the variable 'presence of large-scale landowner land use' was added, the multivariate model took the following form:

$$\text{Probability of fire} = f(\text{rainfall, presence of swamps, elevation, presence of undisturbed forest, presence of large-scale landowner land uses, type of large-scale landowner land use, development stage of large-scale landowner land use, smallholder area, distance to roads, allocation zone, province}) \quad (2)$$

For the non-dry year, the explanatory power of the model was weak ($\rho^2 = 0.04$; Table 4). It was higher but still weak for the dry year ($\rho^2 = 0.09$; Table 5). The overall model did not fully explain fire patterns in all four provinces, supporting the findings of the bivariate analyses that few variables were strongly associated with fire in all provinces. Fire occurrence was determined by interacting factors of varying importance in different environmental, land-use or socio-political settings, especially for Riau in the dry year and Lampung in both years. There were only a few significant determinants of fires in the non-dry year. In the dry year, more factors were

Table 4 Logistic regression for 1999. The odds ratio for the significant parameters is calculated as the odds of the parameter divided by the odds of the parameter in the variable compared to column. Significance level: *** $p < 0.01$, ** $p < 0.05$, ns = not significant.

Variable		*n*	χ^2		*Odds*	
					Variable compared to	*Odds ratio*
Intercept		1	60.78	***		
Decrease in fire probability						
Rainfall	medium	1	1.82	ns	High	
Allocated but not used by large-scale landowners	Production zone	1	19.28	***	Non-allocated zone	0.68
Distance to roads	0–5 km	1	5.81	**	15–20 km	0.77
Rainfall	medium-high	1	0.38	ns	High	
Swamp		1	1.36	ns	Other areas	
Tree-crop plantation	Established before 1992	1	0.32	ns	Other areas	
Logging concession		1	0.54	ns	Other areas	
Province	Jambi	1	2.16	ns	Sumatera Selatan	
Increase in fire probability						
Distance to roads	10–15 km	1	5.22	**	15–20 km	1.38
Province	Lampung	1	9.95	***	Sumatera Selatan	1.67
Smallholder zone		1	10.03	***	Other areas	1.98
Elevation	50–100 m	1	22.38	***	>100 m	2.23
Presence of large-scale landowners		1	10.82	***	Other areas	2.24
Undisturbed forest		1	35.51	***	Other areas	2.58
Province	Riau	1	0.50	ns	Sumatera Selatan	
Timber plantation		1	0.34	ns	Other areas	
Distance to roads	5–10 km	1	0.29	ns	15–20 km	
Transmigration	Established before 1992	1	0.98	ns	Other areas	
Allocated but not used by large-scale landowners	Conversion zone	1	0.35	ns	Non-allocated zone	
Transmigration	Established after 1992	1	0.73	ns	Other areas	
Tree-crop plantation	Established after 1992	1	2.77	ns	Other areas	
Elevation	0–50 m	1	2.01	ns	>100 m	

Table 5 Logistic regression for 1997. The odds ratio for the significant parameters is calculated as the odds of the parameter divided by the odds of the parameter in the variable compared to column. Significance level: *** $p < 0.01$, ** $p < 0.05$, ns = not significant.

Variable		*n*	χ^2		*Odds*	
					Variable compared to	*Odds ratio*
Intercept		1	22.01	***		
Decrease in fire probability						
Province	Riau	1	155.83	***	Sumatera Selatan	0.06
Rainfall	Low	1	35.00	***	Medium	0.37
Distance to roads	0–5 km	1	22.51	***	15–20 km	0.39
Distance to roads	5–10 km	1	31.04	***	15–20 km	0.39
Allocated but not used by large-scale landowners	Production zone	1	143.28	***	Non-allocated zone	0.40
Distance to roads	10–15 km	1	5.98	**	15–20 km	0.69
Province	Lampung	1	86.01	***	Sumatera Selatan	0.88
Province	Jambi	1	1.64	ns	Sumatera Selatan	
Tree-crop plantation	Established after 1992	1	0.25	ns	Other areas	
Logging concession		1	0.87	ns	Other areas	
Increase in fire probability						
Swamp		1	5.40	**	Other areas	1.22
Small-holder zone		1	4.60	**	Other areas	1.35
Timber plantation	Established before 1992	1	8.24	***	Other areas	1.50
Allocated but not used by large-scale landowners	Conversion zone	1	20.50	***	Non-allocated zone	1.61
Elevation	50–100 m	1	28.54	***	>100 m	1.76
Presence of large-scale landowners		1	22.27	***	Non-allocated zone	1.91
Tree-crop plantation	Established before 1992	1	15.72	***	Other areas	2.00
Undisturbed forest		1	118.56	***	Other areas	3.07
Transmigration	Established before 1992	1	0.04	ns	Other areas	
Elevation	0-50 m	1	0.94	ns	>100 m	
Transmigration	Established after 1992	1	0.65	ns	Other areas	

found significant. In the model, drought thus interacted with other factors to cause an increased association between fire occurrence and landscape factors.

The results for the non-dry year (Table 4) were consistent with the bivariate analyses but with a few differences. An increase in fire probability was found in areas mapped as: undisturbed forests (this variable increased the odds of fire 2.6 times compared to other land covers); having large-scale landowners present (fire odds increased 2.2 times compared to areas without large-scale landowners); being at medium altitudes (fire odds increased 2.2 times compared to high altitudes); being used by smallholders (fire odds increased 2 times compared to non-smallholder areas); and being far from roads. A decrease in fire probability occurred in areas allocated to production zones (fire odds decreased 1.47 times), and close to roads (fire odds decreased 1.33 times). Further, the regression showed that Lampung had a much higher fire occurrence compared to the other provinces.

For the dry year, the multivariate model (Table 5) showed that an increase in fire probability was also associated with the presence of undisturbed forests (fire odds increased 3 times compared to other land covers), presence of large-scale landowner land uses such as well-established timber and tree-crop plantations (fire odds increased respectively 2.0 and 1.5 times compared to non-plantation area), medium altitude (fire odds increased 1.8 times compared to high elevation areas), land allocated to conversion (fire odds increased 1.6 times compared to non-allocated areas), smallholder areas and swamps. The regression further indicated that proximity to roads and allocation to production were associated with decreased fire probability. There was thus no evidence of an increase in fire occurrence caused by accidental fires started by passers-by along roads in dry years. Further, in the dry year, fire probability was lower in the provinces of Riau and Lampung than in the non-dry year.

DISCUSSION

The approach in this study had several limitations related to the modelling design and to data quality. The spatial model used here only incorporated spatially-explicit and easily-measurable factors causing fires. For example, lightning was not represented as a potential cause of fire in the model. Other non-spatial variables, such as the socio-political changes that took place in Indonesia in 1997 that empowered smallholders, were equally ignored. The modelling approach thus identified proximate causes and spatial determinants of fires rather than underlying driving forces. By its spatial nature, the model also assumed that fires in areas under different land uses were caused by the main users of those areas. This might not always have been the case in practice, for example where there were social conflicts or fires spreading into neighbouring properties. These cases could have been a source of error in attributing responsibility for fire occurrence.

Some of the spatial data used in the study did not perfectly represent actual landscape processes. This could have resulted in an incomplete model. For example, a proxy variable was used for smallholder land use. This proxy was likely to miss smallholder areas that were far from roads, so that the contribution of smallholders to fire occurrence could have been underestimated. Further, not all fires were detected by satellite systems. Ground fires in logging concessions and undisturbed forests, seasonal wildfires in grasslands that generate less heat or very small fires were unlikely to be detected as accurately as the other fires. Also, the data did not allow separation between seasonal fires routinely used for land management and fires associated with one-time land clearing activities.

Causes of fires

Five general spatial determinants of increase in fire occurrence were identified in this study, namely areas with undisturbed forest, areas where large-scale landowners were present, areas allocated to conversion, areas at medium altitudes and smallholder areas. Areas close to roads and areas allocated to production forest also had decreased fire occurrence. Interannual variability in annual rainfall was a further major determinant of fire occurrence. There was a sharp increase in fires in conversion areas in the dry year, indicating that opportunity to clear land was a strong determinant of fires. Land managers can profit from exceptionally dry conditions by opening large tracts of forest at low cost using fires. Droughts seemed to favour increased fire occurrence, even where fires would not occur under normal climatic conditions (Nepstad *et al.* 1999, 2001). In the non-dry year, the highest increase in fire probability was in undisturbed forest. Since undisturbed forests are naturally resistant to fire, especially in non-drought conditions (Goldammer & Seibert 1990; Kauffmann *et al.* 1988; Cochrane & Schulze 1998), this indicated that land-use changes were ongoing in these forest areas. The type and stage of land use in large-scale landowner areas also determined fire activity. Recently established transmigration sites, logging concessions and plantations were associated with a high fire activity.

The results highlight the importance of land use and land-use policies, together with climatic drought, in driving fires (see also Glover & Jessup 1999; Vayda 1999; Bowen *et al.* 2000; Siegert *et al.* 2001). The 1997/1998 fires resulted from poor forest management and weak fire control, coupled with a severe, but not unprecedented drought (Glover & Jessup 1999). Political, economic, physiographic, sociocultural and institutional factors also contributed to fire occurrence, in addition to the direct and immediate causes of burning, and indirect or influencing factors such as climatic variations (Tahir Qadri 2001).

The focus of this study was on fires associated with land use, either as part of land clearing activities or caused by accidents and negligence; however, a small fraction of the fires detected were likely to be caused by lightning. In this case, only fire propagation and not fire ignition is related to natural and cultural landscape attributes. Fires that are used seasonally to burn agricultural residues or clear the vegetation understorey around settlements were also discounted and, most probably, not detected by remote sensing. The approach adopted in this study also assumed that land-use factors causing fires were mediated by decisions of agents. Attributes governing human behaviour in relation to fire, such as attitudes or environmental perception, were not made explicit, however, cultural and social factors are likely to have affected individuals' perceptions of the impact of fires on the environment and, therefore, fire probability. Agent-based models of fire ignition developed on the basis of in-depth household surveys would be an interesting complement to the model of landscape determinants of fires developed here.

Pathways of land-use fires

Despite the interprovincial variability in determinants of fires, some typical pathways associated with land-use fires and different fire regimes can be recognized. These were similar in all provinces and for both years. An initial step in these pathways was the allocation of forest by the government, through land-use policies. Land allocation to large-scale landowners can result in two different uses (Fig. 1), namely exploitation of logging concessions, or timber or tree-crop plantations. Each use was associated with a different fire regime. Logging concessions were not very much affected by fires, and only had small scattered fires caused by accidents or created to improve access; during a dry year, fire occurrence increased. By contrast, large-scale burning was much more likely to take place in areas allocated to plantations, in order to clear land before planting. When a drought took place, as in the El Niño year, there was a strong increase in fire density in conversion forests (i.e., forests allocated to timber or tree-crop plantations). This was partially a result of accidental fires, but also a consequence of the greater clearing opportunities for companies in highly flammable forests.

The low fire occurrence in logging concessions found in this study is in contrast with the findings of Nepstad *et al.* (1999) and Cochrane (2001) in the Brazilian Amazon, and of Siegert *et al.* (2001) in East Kalimantan, where logged forests had a higher risk of fire. In the present study, while logged-over forest had a greater vulnerability to fire, the presence of an active logging concession may have led to the application of fire prevention measures by the company, therefore decreasing fire probability. The natural flammability of logged-over forest may thus be of less relevance than human intervention in controlling fire ignition.

The total area of land allocated to large-scale landowners by national policies was relatively small in densely-populated provinces with little forest cover left, while it was much larger and occurred mostly in swamp areas in sparsely-occupied provinces. The flammability of these swamps was very low in normal years, but became high under drought conditions. The combination of land allocation and drought thus led to extensive and long-lasting fires. After this initial stage, tree-crop and timber plantations remained vulnerable to fires during droughts.

Areas not allocated to large-scale landowners followed a different pathway. Smallholders could exploit these areas, and the risk of fire during non-dry years was similar to that for plantations. The fire regime in these areas resulted in small but frequent fires. Fire occurrence increased in these areas in the dry year, although not as much as in plantations. In fact, fire control by land managers appears greater in smallholder areas, even though fires were still used for land management purposes (Suyanto *et al.* 2000). Smallholders were probably better than large-scale landowners in protecting their land against fire and thus fewer large fires occurred in these areas.

A third cause of land-use fires was associated with forest cover. The highest fire probability was found in undisturbed forests that were not used by large-scale landowners and were far from roads, despite the low natural vulnerability to fire of these forests (Goldammer & Seibert 1990; Kauffmann *et al.* 1988; Cochrane & Schulze 1998). Apparently, the attraction of undisturbed forests for conversion was very large, as a result of illegal clearing activities and possibly of fires escaping control. Smallholders and large-scale landowners could both use these forests, although inaccuracy in the land cover map could also explain this observation. Areas mapped as undisturbed forest could have been under use by logging or plantation companies. This, however, would confirm the conclusion that logging and agricultural activities disturb a larger area than is generally thought.

Interprovincial differences

Interprovincial differences in predisposing conditions and land availability for agricultural expansion or logging had an influence on fire risk. Lampung is a well-established community and currently experiences few land-use conversions. The high accessibility and large population in Lampung gave this province a relatively high fire occurrence in the non-dry year but a decrease in fire density in the dry year compared to the other provinces. Fires in this province were thus unlikely to be caused by accidents.

By contrast, Jambi and especially Riau are frontier provinces, with large opportunities to expand agricultural and tree-based land uses. Until recently, no large-scale developments took place in these provinces. Land availability motivated the recent expansion of logging activities and plantation crops and this was associated with high fire activity, especially in the dry year. Riau showed exceptional fire behaviour, since fires occurred all across the landscape, independent of climatic conditions. In fact, Riau was the only province where annual fire numbers did not correlate with annual averaged rainfall. According to Potter and Lee (1999), more than 1.5 million ha in Riau were agreed to be converted to plantations after 1995. Further, Bowen *et al.* (2000) found that, in Riau alone, 261 tree-crop estates were operating and that these concessions will, in the near future, represent 2 million ha of tree-crop plantations. Large plantations apparently expanded outside their allocated zone, causing widespread fires (Anderson & Bowen 2000). The pressure to clear land seems to have overwhelmed the climatic control of fires in this province.

Sumatera Selatan had low fire occurrence in non-forest areas and very high fire densities in logging concessions, in agreement with the findings of Bombard and Guizol (1999). This difference with the other provinces was probably caused by the low accessibility of non-forest areas in this province and the high accessibility of logging areas. In the non-dry year, the differences in fire density between types of forest uses were smaller than for the dry year. The accessibility might be the prerequisite for the ignition factor that is required to burn these areas, especially swamps.

CONCLUSIONS

Our view that fire is caused by large-scale landowner and smallholder land uses resulting from land-use policies (Schweithelm 1998; Potter & Lee 1999; Sargeant 2001) was corroborated. Drought acts as a catalyst that reinforces the impact of these forces on land-use fires. While this study highlighted the interaction between land allocation, land-use conversion and fires, the data did not suggest that many fires were caused accidently along roads.

Forests not used by large-scale landowners, generally perceived as being fire resistant, were strongly affected by fires. This suggests that agricultural expansion by large-scale operations and/or smallholders is taking place in areas that are not mapped as being used for those activities, but are not protected. Colonists were either using fire for forest clearing or had altered forest cover on a large scale through illegal logging, making it more prone to fires. Unmapped illegal logging has already been found to be present on a large scale in Indonesia (Jepson *et al.* 2001). Most fires in the provinces studied resulted from the interaction between government policies, which allocate land for specific large-scale landowner land uses, biophysical conditions that increased susceptibility to fires, and occasional droughts that facilitated the opportunistic use of fires for forest clearing, with some fires escaping control.

ACKNOWLEDGEMENTS

This study was started and supported by the World Agroforestry Centre (ICRAF) *Alternatives to Slash-and-Burn* programme, the United Nations Educational Scientific and Cultural Organization (UNESCO) and the Centre for International Forestry Research (CIFOR). It was further helped by the United States Forest Service Remote Sensing facilities (USFS-RSAC), Salt Lake City, USA. We are grateful to S. Henry, S. Vanwambeke and two anonymous reviewers for their comments on the manuscript.

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