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Fire, People and Pixels: Linking Social Science and Remote Sensing to Understand Underlying Causes and Impacts of Fires in Indonesia

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This study in the wake of 1990s fire catastrophes identifies and analyzes underlying causes of vegetation fires in eight locations across Borneo and Sumatra. Multidisciplinary and multiscale analysis integrates geospatial technologies with varied social research approaches and participatory mapping. It helps fill a void of site-specific evidence on diverse underlying causes of the Indonesian fires, despite emerging consensus on macrolevel causes and impacts, and policy debates on preventing future fire disasters. Our most important findings include confirmation of multiple direct and underlying fire causes at each of the eight locations, no single dominant fire cause at any site, and wide differences in fire causes among sites. Conclusions emphasize the importance of location specific studies within a regional analytical context. Our "hybrid" research methods demonstrate the explanatory power of integrating geospatial and social analysis techniques, and the benefits of analyzing fire causes and impacts at multiple scales in varied locations across diverse regions.

KEY WORDS: fires; underlying causes; remote sensing; GIS; participatory mapping; Indonesia.

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INTRODUCTION

Fire has long been a feature of the humid tropical landscape of Indonesia as a tool in farming or land clearing, as a weapon in social conflict, or as a result of accidental or unintended actions (Tomich *et al.*, 1998a). However, since the "Great Fire of Borneo" in 1982–1983, large-scale fires have become an increasingly significant feature of landscape disturbance and deforestation in western Indonesia (Malingreau *et al.*, 1985; Siegert *et al.*, 2001b). In addition to climatic factors, evidence from Indonesia and the Amazon suggests that increased logging and large-scale developments in tropical rainforests, and an extension of modified forest in general, have led to an increased fire vulnerability and incidence by creating a positive-feedback loop whereby fire-affected forest becomes more prone to repeat fire damage (Cochrane *et al.*, 1999; Nepstad *et al.*, 1999; Siegert *et al.*, 2001b).

The worst fires in recent times occurred during the 1997–1998 El Niño-induced drought when at least 11.7 million hectares of forest, farmland and other vegetated land in Indonesia were destroyed or badly damaged (Asian Development Bank, 1999; Tacconi, 2003). The effects of this environmental and humanitarian disaster were felt across the region as smoke and haze, and the fires themselves adversely affected the health, property and livelihoods of some 75 million people (Barber & Schweithelm, 2000). The economic costs exceeded US$ 6 billion with carbon emissions high enough to elevate Indonesia to one of the largest global polluters (Asian Development Bank, 1999; Glover & Jessup, 1999; Page *et al.*, 2002; Tacconi, 2003).

Specific national-level reforms in land-use planning policies to address risks of large-scale land clearing and burning have been recommended by a diverse array of Indonesian forestry and environmental officials, non-governmental environmental organizations, international aid and technical organizations, and governments of neighboring nations (Murdiyarso *et al.*, 2004). Many of these focus on ways to eliminate all land-clearing fires on peat land, and call for site-specific assessments of risks of land-clearing or land-use "conversion," whether or not it involves burning (Applegate *et al.*, 2001; Barber & Schweithelm, 2000; Tacconi, 2003). Under reforms after 1998 and the regional autonomy regulations since 2001, numerous land allocation processes suddenly devolved to provincial and district governments. Environmental and indigenous rights advocacy groups have insisted on land-use decision making processes that directly address the inherent conflicts between commercial land developers and customary communities, as well as others managing land for local livelihoods or conservation (Tomich *et al.*, 1998a). However, no simple policy solutions or technical innovations will address these diverse causes of fire, or prevent disastrous fires from recurring.

Defining Direct and Underlying Causes of Fires

Many of the debates on appropriate action to prevent future fire disasters focus on the contentious problem of fixing blame for these catastrophic fires. Problematic areas in these heated controversies highlight the importance of distinguishing direct causes of specific fires from the underlying social, as well as meteorological and ecological, causes of fires. For the purposes of this research, direct causes are human activities or immediate actions at the local level, which originate from intended fire uses, and immediate consequences of fire accidents related to intended fire uses, which directly cause fires. They include the specific circumstances of fire ignition for specific fire events, and immediate contributing factors to decisions about what, where, when, and how to burn, and about steps (if any) taken to control specific fires. Underlying causes are driving forces, especially fundamental social and political processes, such as land-use control institutions, investment patterns, and regional development policies, which underpin the direct causes and either operate at supralocal level or have an indirect impact from the national level or broader regions (Geist and Lambin, 2002). While underlying causes unquestionably also include meteorological conditions, including the El Niño phenomena, as well as underlying ecological conditions, the focus of this study was limited to more immediately human-induced phenomena.

Vayda (1999) showed that direct causes of the fires are many and varied. The extensive national and regional media coverage of the 1997–1998 fires and the region-wide "haze" they produced prompted increased attention to addressing broad, underlying causes of fires and smoke. The government initially blamed the fires on the El Niño drought and smallholders' shifting cultivation (Anon, 1997) but evidence from satellite imagery and maps of active fires (hot spots) indicated that the most extensive fires and the greatest amounts of smoke originated from government sanctioned corporate plantation development, logging concessions, and large-scale land-clearing/development projects (Hoffmann *et al.*, 1999; Potter and Lee, 1998a; Stolle *et al.*, 2003). Yet, as a fuller picture of the diversity of fires and of their wide-ranging impacts has emerged, it is clear that fires occurred at multiple scales and for many reasons, and that varying impacts on local communities and forest had a variety of complex underlying causes (Applegate *et al.*, 2001; Bowen *et al.*, 2000).

Remote Sensing of Indonesian Fires

Many remote sensing studies calculated the extent of the fires through the interpretation of active fires from NOAA AVHRR (National

Oceanographic and Atmospheric Administration Advanced Very-High Resolution Radiometer) imagery and burn scars identified on a range of satellite imagery (Legg and Laumonier, 1999; Liew *et al.*, 1998; Malingreau *et al.*, 1985). Some studies also included supporting data on official land use to identify possible reasons for burning (Siegert and Hoffmann, 2000; Stolle *et al.*, 2003). The burnt area estimates[1] and findings of these macrolevel studies are still much cited and there is no doubt that they were extremely useful in providing a timely picture and analyses of the extent of the fires. However, critics rightly point out that satellite imagery or "fire hot spots" analyzed in isolation "lack the textured understanding of social landscapes and the role they play in creating fire hazards" (Harwell, 2000), and are of minimal use on their own in formulating policies for preventing or managing fires (Robbins, 2003).

A wide range of recent research demonstrates the increasing use of remote sensing and geographic information systems (GIS) by social and environmental scientists as tools in understanding how human decisions about land use, and the institutions in which they are embedded, influence rates and characteristics of land-cover change (Brondizio *et al.*, 1994; Dennis *et al.*, 2001; Fairhead and Leach, 1996; Mertens *et al.*, 2000; Turner *et al.*, 2001). Some, however, believe that quantitative methods of spatial analysis provided by geospatial technologies, representing positivist science, can offer little to understanding cultural landscapes (Philo *et al.*, 1998). Others assert that those familiar with local contexts who utilize spatial technologies possess a powerful set of analytical tools to understand culture–landscape relationships (Jiang, 2003; Turner, 2003). The literature has few examples of the integration of social science and remote sensing as applied to the cultural dimension of vegetation fires. One study of savanna burning from Mali highlights the benefits of a hybrid approach that links the results of surveys and interviews with burn scar analysis of Landsat Thematic Mapper (TM) imagery (Laris, 2002). This study showed that developing a nuanced understanding of the local dynamics of large-scale phenomena with social and ecological implications of global as well as regional importance demands such a "hybrid" approach.

Joining Techniques in Fire Research and Policy

Developing effective means to prevent future fire disasters in Indonesia requires overviews of fire dynamics and landscape impacts based on

[1]These estimates are not complete in their geographical scope and are not easily comparable as different interpretation techniques and imagery were used in the individual studies.

analysis of the "big picture" in terms of changing landscape and climate, and of macrolevel social, political, and economic considerations. Combining these with information defining important local parameters of change and identifying rationales underpinning the human actions that have largely brought about these changes locally will help develop the insights necessary to understand complex causal relationships and complex and varied chains of impacts.

Despite an emerging consensus on the macrolevel causes and impacts of the "fire problem" there is still a lack of published in-depth empirical evidence on the underlying causes and impacts (Barber and Schweithelm, 2000; Harwell, 2000; Potter and Lee, 1998a). The multidisciplinary approach we developed for our research and analysis integrates remote sensing and geospatial technology with social research and rural assessment methods, including participatory mapping at a landscape scale (usually a region of between 50,000 ha and 2,50,000 ha) encompassing up to several dozen settlements and considerable ecological variation. These methods allowed us to develop relatively detailed histories of fire impacts and of landscape transformation in several areas, and more general information at the regional and island scale covering at least the periods before and after the 1997–1998 fires in all areas, and periods back to the late 1970s in some locations. We aimed to answer questions about the varied characteristics of fires associated with their locations, perpetrators, reasons for burning, and reasons for fire outcomes. This would allow us to identify patterns to classify the diversity of fires in Kalimantan and Sumatra, and would support practical means and policy development to prevent future fire disasters

STUDY AREA

We selected four study sites in Sumatra and four sites in Kalimantan (Indonesian Borneo) with different historical land-use patterns, which experienced different types of fires in the late 1990s, and which represent a diverse range of fire impacts on communities, landscapes, and ecosystems. Figure 1 shows study site locations and Table I summarizes the site characteristics. For further details refer to the individual site reports[2] (Colfer *et al.*, 2000; Dennis *et al.*, 2000a; Dennis *et al.*, 2000b; Mayer and Suratmoko, 2000; Mayer *et al.*, 2000; Suyanto, 2000; Suyanto *et al.*, 2000a,b; Suyanto and Ruchiat, 2000; Suyanto *et al.*, 2000c,d).

[2]Site reports are available for download at http://www.cifor.cgiar.org/fire-project/index.htm.

Table I. Site Characteristics

Site	Site(ha)	Physical landscape	Land-use	Satellite image time series	Remote sensing analysis level
Site 1 (Sekincau)	51,610	Mountainous	Small holder coffee: Bukit Barisan Selatan National Park: illegal logging	1985–1994–1997 Landsat MSS, TM	Site/landscape–full image scene-regional fire hot spot
Site 2a (Menggala peneplains)	72,524	Peneplains	Ex-logging concession: corporate timber plantations: transmigration project	1984–1999[1] Landsat MSS, TM	Site/landscape-regional fire hot spot
Site 2b (Menggala swamps)	79,732	Swamps	Corporate oil palm plantations: transmigration project: traditional swamp rice farming	1984–1999 Landsat MSS, TM	Site/landscape-regional fire hot spot
Site 3 (Musi Banyu Asin)	253,401	Coastal swamps	Logging conces-sion:transmigration scheme: illegal logging: fishing	1986–1992–1998 Landsat MSS, TM	Site/landscape-full image scene-regional fire hot spot
Site 4 (Tanah Tumbuh)	129,200	Low-lying plains and uplands	Ex-logging concession: corporate: smallholder rubber agroforestry and field crops	No image analysis	No image analysis
Site 5 (Danau Sentarum)	197,000	Peat swamp forests and uplands	Danau Sentarum National Park: fishing: indigenous shifting cultivation and agroforestry	1973–1990–1997 Landsat MSS, TM/SPOT XS	Site/landscape-regional fire hot spot
Site 6 (Sanggau)	211,808	Uplands: plains	Indigenous shifting cultivation and agroforestry: corporate oil palm and timber plantations: transmigration projects	1991–2000 Landsat TM	Site/landscape-regional fire hot spot

Table I. Continued

Site	Site(ha)	Physical landscape	Land-use	Satellite image time series	Remote sensing analysis level
Site 7 (Tumbang Titi)	871,616[2]	Uplands: plains: peat swamp forests	Indigenous shifting cultivation and agroforestry: corporate oil palm and timber plantations	1989–1996–1998 Landsat TM, ERS SAR[3]	Full image scene-regional fire hot spot
Site 8 (Long Segar)	218,305	Uplands: riverine	Ex-logging concessions: corporate oil palm and timber plantations: transmigrations project: Indigenous shifting cultivation and agroforestry	1983–1990–1998–2000 Landsat MSS, TM[4]	Site/landscape-regional fire hot spot

[1] Half of Site 2a (38,913 ha) is covered by time series 1984–1986–1994–1999.
[2] Image analysis carried out at the TM image level not at landscape. Trajectory of change analysis not carried out due to poor quality imagery.
[3] SAR—Synthetic Apeture Radar onboard the European Space Agency Satellite (ERS-1)
[4] Original site study 1990–1998, (Colfer *et al.*, 2000), extended with the years 1983 and 2000 in an extgension of the study Dennis and Colfer (In press).

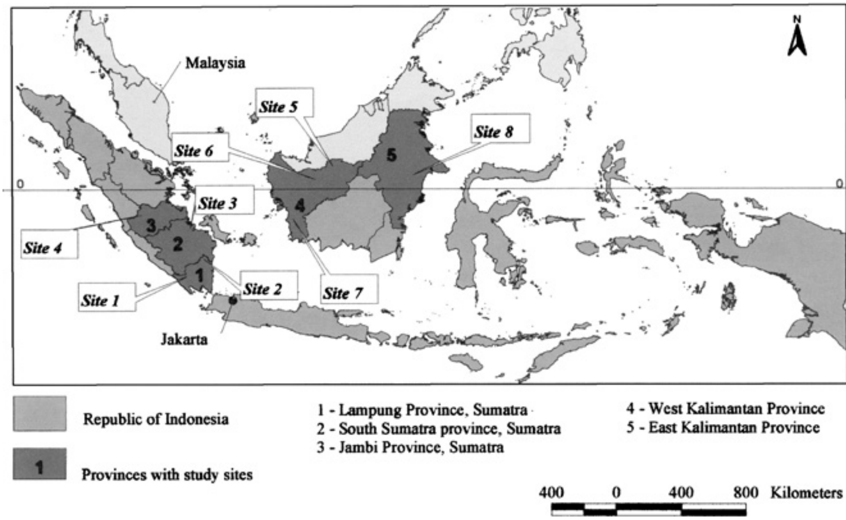

Fig. 1. Location of research sites.

METHODS

We combined fine-scale remote sensing data (Landsat TM and/or SPOT Multispectral (XS)) and hot spots (active fires) data (from NOAA AVHRR) with detailed information from interviews, participatory sketch mapping, and baseline information for a select number of locations, usually representing a subset of villages, resource concession areas, or designated conservation areas within the larger site.

Site Selection Procedure

We delineated study site boundaries based on a combination of jurisdictional, ecological, and remote sensing factors. The sites were not selected to document causes of the most extensive fires of the late 1990s, or the fires that generated the most smoke, nor were they chosen to heap detailed blame on "the usual suspects." Due to the importance to this study of information drawn from interviews and narratives concerning sensitive topics related to fire, and on land-use mapping by members of local communities, our selection of sites prioritized locales where we believed credible information would be available from research partners. In many cases, for subareas within the sites, detailed fire-related information was

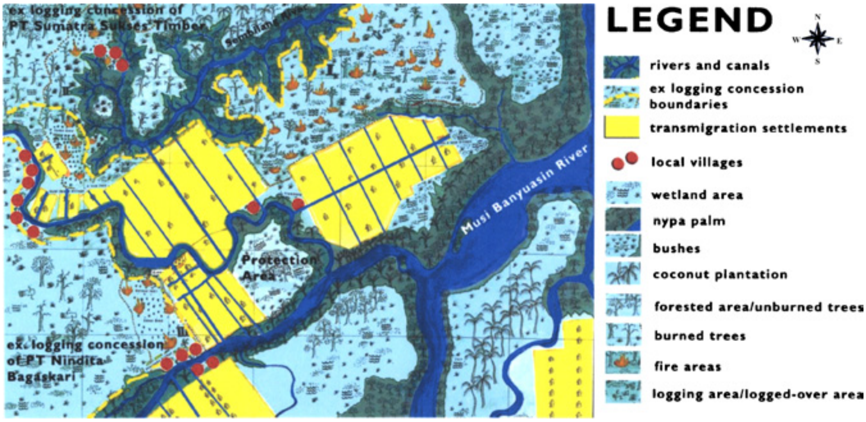

Fig. 2. Musi Banyu Asin (MUBA) landscape-scale sketch map. Width of map approximately 60 km.

available from official sources, previous research, and local knowledge gained through Nongovernmental Organizations (NGO) activities.

Social and Ethnographic Research

We employed social research methods aimed at documenting specific fire events in particular locations, as well as understanding the extent to which the causes of fires are influenced by land-use policies and practices from the village level through regional authorities and the central government, from household resource and fire-use decisions through transnational investments. Ethnographic methods intended to construct a picture of relationships among land users, land managers, and fire in each of the sites included household surveys, group and individual interviews, participatory sketch mapping and field surveys, and a range of rural appraisal exercises. In Sekincau, Danau Sentarum, Sanggau, Tumbang Titi and Long Segar, researchers undertook village level analysis in addition to landscape level analysis. In most of the sites, local NGOs assisted with the social surveys. Representatives of a broad range of stakeholders were interviewed including various groups within local communities, government officials, and large landholders or concession holders.

Members of local communities were usually interviewed in their homes, at homes of village leaders, or in village meeting halls. In a typical village interview situation, core researchers and regional NGO research partners invited formal and informal leaders to attend a number of meetings where discussion included explanations of the research purposes, consultations on research methods, general information about the village, land and resource uses, and settlement history. Further discussion included specific issues related to fires, such as the village's resource use and fire history, resource management concerns, and conflicts or controversies with neighbors or within the village with implications for fire causes or impacts. Rapid Rural Appraisal (RRA) techniques, such as participatory sketch mapping were used (see Fig. 2). In several sites, sketch maps previously produced through collaborations with regional NGOs or other research efforts were used as a base for discussions. Ensuing discussions referring to these maps elicited detailed information about specific fire events, including fire locations, dates and duration, specific details about fire ignition including identities of fire starters and reasons for burning, burning or fire management practices employed, direction of fire movement, and local narrators' hypotheses about fire origins, as well as their assessments of fire causes and results. Drafting and discussions of sketch maps were followed by field surveys with village members to map locations of fire events and resources of particular concern to this study using a hand-held global positioning system (GPS). The sketch maps also identified areas of conflict, often where customary land or resource use boundaries overlapped with official land-use designations.

Government officials were usually interviewed in their offices about locations of major fires and official assessments of causes, fire prevention activities by government agencies, and fire suppression capacity. Officials also provided researchers with maps of fire-related and resource industry-related information, as well as documents related to fire prevention or fire suppression policies. Because this research was conducted in the early phases of reform-era "regional autonomy" experiments, many of the regional officials interviewed were new to their positions, and many key decision makers of 1997–1998 were unavailable, or unwilling to comment on government positions, capabilities, and activities of that time.

Large landholders or managers of companies holding plantation or logging concessions were usually interviewed in site offices or company regional headquarters. Researchers had ostensibly free access to most company sites. However, some companies effectively limited researchers' access to their working areas.

Spatial Data Analysis

Secondary spatial data and remotely sensed imagery were collected for the sites. These data included topographic maps,[3] administrative

[3] Available from the national mapping agency (BAKOSURTANAL) at a scale of 1:50,000 or 1:250,000.

boundaries,[4] land/forest cover,[5] land/forest use status,[6] and official spatial planning boundaries.[7] Multitemporal series of remotely sensed imagery were also collected and included Landsat TM, Landsat Multi Spectral Scanner (MSS), SPOT XS, and in one instance Synthetic Aperture Radar imagery. In general, these image datasets covered two to three dates from the mid-1980s to the late 1990s, including one date after the 1997–1998 fires (see Table I). We also extracted active fire locations from lower resolution NOAA AVHRR imagery to provide a general fire history and fire frequency for each site, and for Sumatra and Kalimantan as a whole (Stolle, 2000). For a discussion on the accuracy hotspots refer to Stolle (2000). In addition, processed "hot spots" were also kindly provided by a number of bilateral forest fire projects.[8] Aerial observations were carried out in 1999 over three of the sites producing high-resolution geo-located digital photography.

Remote sensing (image processing) and spatial analysis techniques were used to classify and analyze the historic and current patterns of land cover and burn scars for each site (Lachowski and Maus, 1995). We used PC ER Mapper for image processing and ESRI PC ArcView and image classification and spatial analyses. Imagery was geometrically corrected and spectrally contrast enhanced and various band combinations assessed so that colors that appeared on our working satellite prints would make intuitive visual sense to social scientists working in the field.

We classified the image sets for each site by on-screen digitizing of digital imagery (Achard *et al.*, 2002; Boehm and Siegert, 2001; Dennis and Kurniawan, 2000; Siegert *et al.*, 2001a). For each site, the land cover on the oldest image was classified first and then this classification served as a template to update land cover from the images of subsequent dates.

[4]We preferred to use the most locally available source, which was usually from the provincial planning agency (Bappeda).

[5]Variety of sources using differing definitions and classification schemes: Regional Physical Planning Programme for Transmigration (RePPProT, 1990) a nation-wide thematic mapping exercise showing land-cover situation in the mid-1980s at 1:250,000 scale, World Conservation Monitoring Centre (1996) modified the RePPProT dataset and made it available on CD; National Forest Inventory (FAO/Ministry of Forestry) showing forest cover for the mid-1990s at a scale of 1:250,000; Forest/Non-Forest (Ministry of Forestry/World Bank) for the mid-late 1990s available in digital form only (Holmes 2000). For a discussion of these data sources see FWI/GFW (2002).

[6]Better known as the "agreed forest land-use categories" (*TGHK – Tata Guna Hutan Kesepakatan*) originally mapped at 1:500,000 scale and published in 1985 (Potter, 1990).

[7]RTRWP (Rencana Tata Ruang Wilayah Propinsi) spatial planning maps produced by provincial planning agency (Bappeda) and available at a scale of 1:250,000 published in the latter half of the 1990s.

[8]Japanese International Co-operation Agency (JICA)—Indonesian Ministry of Forestry (MoF) Forest Fire Protection and Management Project (FFPMP), Bogor, Indonesia; European Union – MoF Forest Fire Prevention and Control Project (FFPCP), Palembang, Sumatra; German Technical Assistance (GTZ) – MoF Integrated Forest Fire Management Project, Samarinda, East Kalimantan.

A standard two-level land-cover/land-use classification scheme was used. First level classes were: natural forest, scrub/grass, plantation, agriculture, settlement, recent burn scars,[9] and water bodies. The second level included density of forest cover, type of plantations, and type of crops.

It is normal practice to provide an estimate of image classification accuracy by comparing it with the actual land-cover types on the ground at the time (Congalton, 1991). However, all of the satellite imagery used in this study was historical and it was thus not feasible to check its accuracy on the ground. As a proxy for conventional accuracy the most recent classifications were checked in the field by researchers accompanied by members of local communities.

Cumulative area estimates were determined for each image classification and "trajectories" of land-cover change were calculated by creating a "from" and "to" matrix of land-cover change between two successive dates. Although these calculations did not provide conclusive indications of the specific causes of changes in the landscape, they did enumerate changes that might be attributable to fire with further analysis, and provided evidence to characterize landscape change between pre-fire and post-fire periods at a scale that would be impossible based on "grounded" social and ecological survey methods alone. These calculations also helped ensure that the smaller areas within each site selected for more detailed study did not represent extremely unusual cases of landscape change within each landscape scale study site.

Integrating Social and Remote Sensing Data

The final stage in the analyses was to integrate the image classifications, burn scar locations, and active fire distributions with the results from the interviews, social surveys, participatory mapping, and information from previous research and secondary sources. This informed our understanding of the occurrence and apparent causes and impacts of fire to landscape and people within each site, and for specific smaller areas within it.

Paper sketch maps produced through participatory mapping exercises and modified by GPS in the field, were scanned and input to the GIS. These digital maps were then overlaid with the land cover/use, burn scars, and

[9]There are two quite different post-fire signals: the deposition of charcoal (char), and the alteration of vegetation structure and abundance, commonly called a burn scar (Pereira *et al.*, 1997). Recent burns have a high composition of charred material and a spectral reflectance that is very distinct from living vegetation. This signal is relatively short-lived and tends to be almost completely erased by wind and rainfall in a few weeks or months after the fire. The second signal is more stable. Over time the spectral reflectance of the burn scar changes, as pioneer and eventually secondary vegetation grows back.

active fire locations generated by satellite image analysis. Using the resulting data layers, we could identify boundary overlaps between different land users, such as areas claimed by local people under customary rights and plantation companies or other officially designated land uses. Estimates of how much land had been burned and suggestions of why were based roughly on the digitized sketch maps and on interviews for each site at the landscape level. In many cases, narratives and comments by local residents and others indicated specific details about particular fire events, including clear indications of both their immediate causes and immediate results and in some cases assertions concerning what we have termed underlying causes. Within the GIS it was possible to identify these burned areas more precisely on the satellite image-derived land-cover maps and calculate the former land cover and the exact size of the burn scar, and thus approximately the area burned in each period for which data were available.

This approach provides a rich record of where and when fires have occurred, how extensive they have been, and resulting changes in land cover and land uses. It indicates causes and impacts of specific fire events and the scope and characteristics of the "fire problem" in general, both as perceived by the people most directly familiar with and most directly affected by fires, and through larger-scale, more generalized remote sensing perspectives.

RESULTS

Direct Causes

The study found that there were a number of direct causes of fire on any one site with the four main direct causes of fire, in order of frequency as: fire used as a tool in land clearing; accidental or escaped fires; fire used as a weapon in land tenure or land-use disputes; and fire connected with resource extraction. In over half of the sites, burning practices to clear land for short rotation swidden were a frequent cause of fires, with burning conducted mainly by smallholders, including longstanding or indigenous populations and recent migrants (Table II). Similarly, over half of the sites provided examples of large landholders using fire as a tool in land clearing for government licensed plantations or transmigration sites, in spite of the central government's 1995 prohibition on commercial burning (Colfer *et al.*, 2000; Mayer and Suratmoko, 2000; Suyanto and Ruchiat, 2000; Suyanto *et al.*, 2000c,d).

The Musi Banyu Asin (MUBA) site clearly shows the sequence from burning to establishment of a transmigration site (Fig. 3). The trajectory of land-cover change analysis, for the same site shows that between 1986 and 1992, 44% (12,690 ha) of land classified as recently burned in 1986 had been developed for transmigration by 1992, with a further 5,532 ha of land cleared by fire for transmigration between 1992 and 1998.

In many of the sites, fires set to clear limited areas of land for plantations of smallholder coffee (Sekincau), oil palm (Menggala, Tanah Tumbuh, Sanggau) or illegal logging (Sekincau) escaped into adjacent open access forest land or young timber plantations. In most cases, the escaped fires spread extensively due to the lack of incentives for people to effectively control fire that was not on their own land. This is clearly seen in Sekincau, where both recent migrants and long-term residents are establishing coffee gardens on a forest frontier previously degraded by illegal logging. The long-term land-cover change trends (Fig. 4) show forests being replaced by coffee gardens or burn scars, with 91% (25,972 ha) of forest cover converted to coffee gardens and 9% appearing as recent burn scars between 1985 and 1994. Some of these fires were intentional, but many burned beyond the limited areas intended by the people who set

Table II. Direct Causes of Fire Listed by Site [Adapted from Applegate *et al.* (2000)]

	Sumatra					Kalimantan			
Direct causes of vegetation fires	1	2A	2B	3	4	5	6	7	8
Fires as a tool in land clearing									
Small holders (indigenous people, migrants)									
Conversion of forests to alternative land uses (e.g. to coffee or rubber)	√				√				
Rotational tree cropping	√				√			√	
Short rotation swidden			√	√		√	√	√	√
Large landholders (companies)									
Large-scale plantation development		√	√		√		√	√	√
Transmigration sites			√	√				√	√
Fire as weapon in land tenure/use disputes									
Arson	√	√			√	√	√	√	√
Accidental fires (Escaped)									
Land clearing/illegal logging	√	√	√	√		√	√	√	
Cooking/smoking/camping	√			√		√	√		
Fire connected with resource extraction									
Improve fishing areas/ search for fish and turtles/access tracks for boats/deer hunting				√		√	√		√

Site 1= Sekincau (Sumatra); Site 2a = Menggala peneplains (Sumatra); Site 2b = Menggala swamps (Sumatra): Site 3 = Musi Banyu Asin (Sumatra); Site 4 = Tanah Tumbuh (Sumatra); Site 5 = Danau Sentarum (Kalimantan); Site 6 = Sanggau (Kalimantan); Site 7 = Tumbang Titi (Kalimantan); Site 8 = Long Segar (Kalimantan).

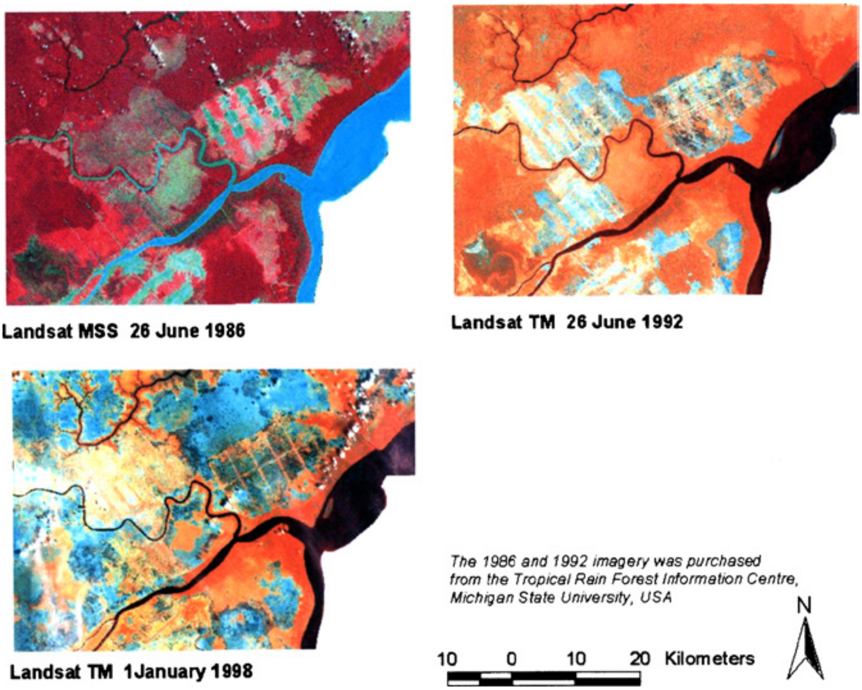

Fig. 3. Musi Banyu Asin (MUBA)-Landsat image time series 1986–1992–1998. Band display combinations are 421 (MSS) and 457 (TM). Red (MSS) and orange (TM) tones indicate vegetation cover, with paler shades representing sparser cover. Pale green tones (MSS) indicate cleared lane, and cyan tones (TM) indicate recent burns. Water is cyan (MSS) and black (TM).

them. The more extensive "accidentally" burned areas are later planted with smallholders' coffee as well (Suyanto, 2000).

Fire used as a weapon in conflicting or overlapping land use or tenure claims was clearly found in seven of the nine sites. Deliberately set fires were reported to be prevalent in many areas rich in commercially valuable resources where land for agricultural production is either becoming scarce and/or where conflicts over resource tenure or resource access and uses occur, or have occurred in the recent past. These types of fire were particularly important in areas with remaining natural forest on fertile soils, and areas where large landholders have obtained land concessions from central or regional governments for oil palm and timber plantations. This scenario is particularly well exemplified in the peneplains of Menggala (Site 2a) where local farmers used fire to claim back land from a plantation company in 1998. The conflict area is highlighted in Fig. 5 (Zone 3) by the presence of

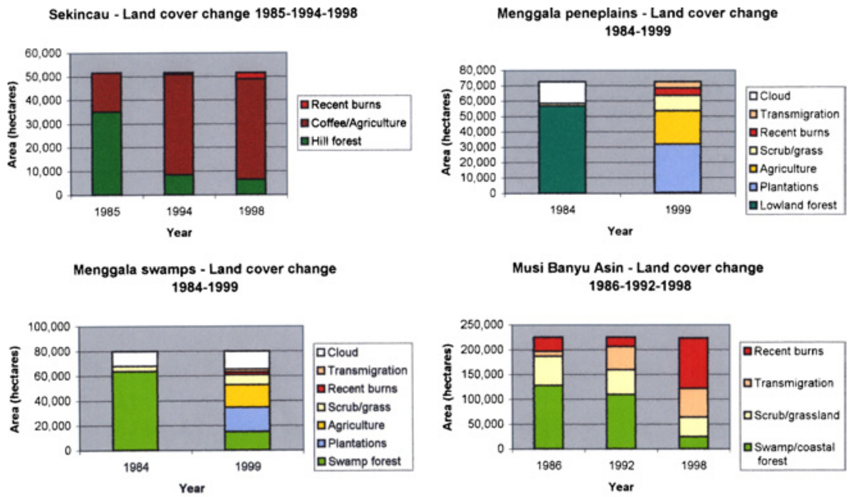

Fig. 4. Cumulative land-cover change estimates for Sites 1, 2a, 2b, and 3, based on satellite image classification for individual years.

a large irregular shaped burn scar within the plantation boundary. Similar fires were also set by smallholders to reclaim land for their own use that had been previously cleared and planted by government-approved concession-holders in the Sanggau and Tanah Tumbuh sites.

Some of the findings most difficult to interpret were cases where local informants asserted that fires that eventually spread to extensive areas within official concessions, and sometimes beyond, had been deliberately set by agents of companies holding plantation development concessions in order to eliminate land claims by local communities. Similar findings also come from a study in East Kalimantan where local residents reported that fires were deliberately set by oil palm company workers specifically to burn the forest gardens of communities adjacent to the plantation in order to reduce the company's financial compensation liability (Gönner, 1999). These fires could be counted as arson, and thus as weapons in resource conflict, or as agricultural land clearing.

On four of the eight sites, we were told that nearby residents and seasonal migrants set fires to facilitate small-scale, seasonal resource extraction, including fishing and deer and turtle hunting. In some cases, these activities specifically took advantage of improved access to dried-out swamps during drought periods. In 1997, the burning of 60,172 ha of degraded swamp forest in the MUBA site was attributed by local informants partly to fires associated with fishing activities, where it is used to clear undergrowth

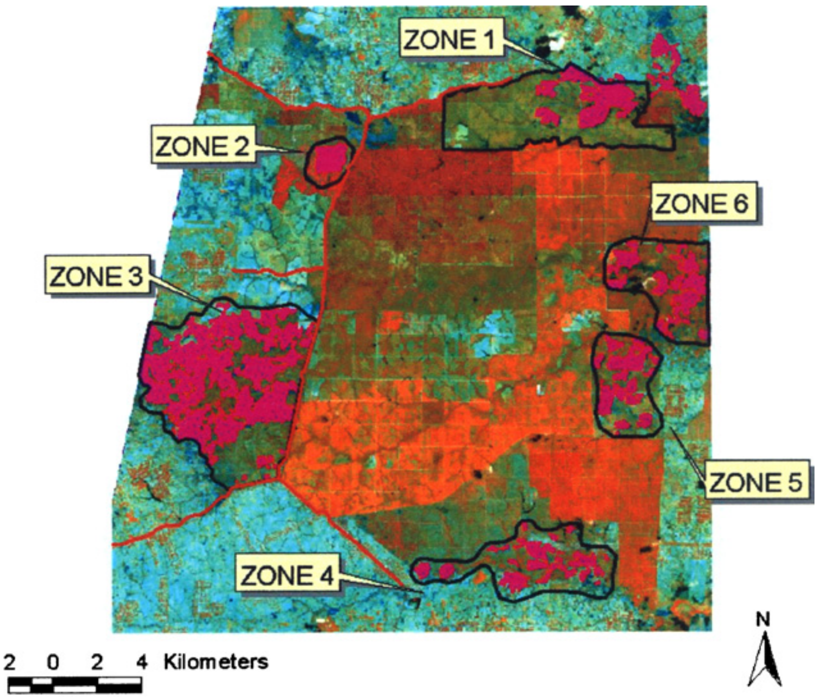

Fig. 5. Burn scar patterns in the Menggala peneplains site, Sumatra. Background image Landsat ETM September 1999 displayed in 4, 5, 7 band combination: cyan – bare fields, orange – corporate plantation tree crop, pink – recent burn scars. Zone 1 – escaped swamp fires; Zone 2 – deliberate clearings clearing by company; Zone 3 – land conflict fires; Zone 4 – land conflict fires; Zone 5 – Land conflict fires; Zone 6 – escaped swamp fires.

for ease of access to small pools rich in fish and sometimes turtles, and in campfires used for cooking the catch. Smaller uncontrolled fires associated with fishing and turtle hunting were also reported by local informants in Danau Sentarum and Long Segar in 1997 (Colfer *et al.*, 2000; Dennis *et al.*, 2000a). An earlier study of the use of fires in resource extraction in the Danau Sentarum area found anecdotal evidence of burning swamp forest to facilitate capture of a valuable ornamental fish species (Luttrell, 1994). Although it is nearly impossible to establish the burden of proof for actual ignition in such cases (as discussed by Vayda, 1999), researchers in Danau Sentarum found compelling evidence that a small fire in dried-out swamp forest had started from a campfire that had not been properly extinguished early that morning.

Underlying Causes

This study identified six major underlying causes of fire. At each site, fire was attributed to more than one underlying cause, as summarised in Table III.

Land Tenure and Land-Use Allocation Conflicts and Competition

By far the most significant underlying cause of fire across the sites was related to land tenure and land allocation competition and conflict (Table II). In Sekincau and Menggala in Sumatra where land was scarce or where smallholders had informal land claims when occupying national park land or disputed land officially designated to other parties, competing claimants sought solutions through the use of fire. Smallholders, including both longstanding local populations and newcomers, have burned natural forest to plant a variety of crops and settle land frontier-style, or to establish or reassert claims over land that had previously been planted by timber or oil palm companies. Local communities in Menggala (Site 2a) burned plantation land to reclaim it for their own use, and reactivate their own claims during a period of political turmoil in 1998. A similar pattern was observed in Tanah Tumbuh, where individuals used fire to prepare land for tree planting that would secure informal recognition of their "private" property claims on lands that the community had previously considered common property.

Another major issue across all sites was a classic "tragedy of the commons"—the lack of incentives for individuals, local communities, or private companies to control unwanted fire on land which was not their own, where they had no secure property rights, and where they had no sense of responsibility for land management and received few direct benefits from investing in fire control. Related to this are overlapping claims and competition for land and natural resources among many stakeholders in areas where actual development patterns are already well-defined and in some cases, in contrast to official plans and designations, such as in parts of Lampung Province, as well as Tanah Tumbuh in Jambi Province. The fire problem in these situations is often related to the lack of an accessible, equitable, and transparent legal system to resolve disputed land and land-use claims.

Inappropriate, inequitable, and uncoordinated allocation of land by multiple government agencies and administrative levels for different uses has resulted in various stakeholders' burning land and forests, either deliberately or by neglecting to control fires they set or discover. Both those authorized by central or regional authorities, and those attempting

Table III. Underlying Causes of Forest and Vegetation Fires for Sites 1–8 [Adapted from Applegate *et al.* (2000)]

	Sumatra					Kalimantan			
Underlying causes of vegetation fires	1	2a	2b	3	4	5	6	7	8
Land tenure and land use allocation conflicts and competition									
Lack incentives for individuals, local communities, or private companies to control unwanted fire on land which was not their own, where they had no secure property rights, and where they had no sense of responsibility for land management.	√	√	√	√	√	√	√	√	√
Overlapping claims and competition for land and natural resources among many stakeholders in areas where actual development patterns are already well defined, and contrary to official plans and designations in some cases.	√	√	√		√	√	√		√
Inappropriate, inequitable and uncoordinated allocation of land by multiple government agencies and administrative levels for different uses.		√	√	√	√		√	√	√
Lack of an accessible, equitable, and transparent legal system to resolve disputed land and land use claims.		√			√		√		√
Informal land tenure security promotes site occupation and forest conversion	√	√							
Forest degrading practices									
Inappropriate timber harvesting practices for site conditions.	√		√	√			√	√	√
Repeated fires due to increased fire proneness of previously burned vegetation.	√		√	√		√	√	√	√
Drainage systems in swamps that lower the water table dry out the peat and provide increased access.			√	√					
Economic incentives/disincentives									
Anticipated high profits of alternative uses to plantation developers, both large corporations and smallholders of forest land following logging (e.g. oil palm, rubber, coffee, timber).	√	√	√		√		√	√	√

Table III. Continued

Underlying causes of vegetation fires	Sumatra					Kalimantan			
	1	2a	2b	3	4	5	6	7	8
Perverse development processes and mechanisms.		√	√		√			√	√
Population growth and migration									
Large-scale government sponsored and spontaneous in-migration	√	√	√	√				√	√
Lack of commitment to new location and careless use of fire									√
Inexperience with use of fire in new environments									√
Different resource (and fire) use patterns by different ethnic groups						√			√
Inadequate fire fighting and management capacity									
Inadequate forest and fire management plans, and facilities to prevent and suppress accidental or escaped fires in plantations and natural forests	√	√		√		√	√	√	√
Lack of institutional capacity, resources and will to monitor and deal with encroachment and other illegal activities in protected forest areas	√						√		

Sumatra: 1 = Sekincau; 2a = Menggala peneplains; 2b = Menggala swamps; 3 = Musi Banyuasin; 4 = Tanah Tumbuh. Kalimantan: 5 = Danau Sentarum; 6 = Sanggau; 7 = Tumbang Titi; 8 = Long Segar.

to contest government land or resource allocations have used fire to try to remove competing land occupants or resource claimants, or to eliminate high-quality native forests whose continuing presence would legally prevent certain types of land development that would require forest clearing. In some instances, central government authorities allocated the same tract of land to different users or concession-holders. In other cases, especially as regional authorities began exercising new perogatives under tentative moves toward administrative devolution in the chaos toward the end of the Suharto period, central and regional authorities issued permission or recognized claims for conflicting uses on the same land. For example, in Tanah Tumbuh, local communities contested allocation of their customary land for development of oil palm plantations in 1994. In ensuing conflicts, fire was used as a weapon by both sides. Plantation developers burned local community members' tree crops (rubber) to reinforce their concession claims,

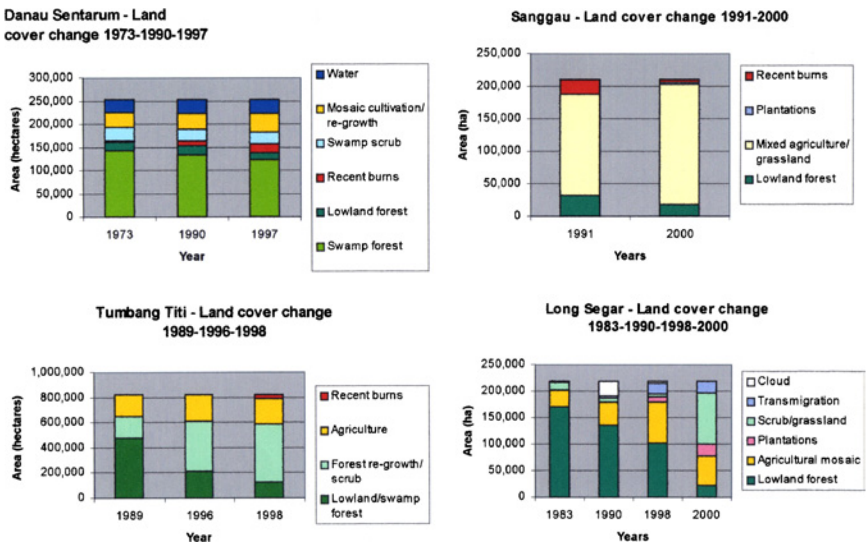

Fig. 6. Cumulative land-cover change estimates for Sites 5, 6, 7, and 8, based on satellite image classification for individual years.

and members of local communities burned plantation crops (oil palm) and a site office. Similar instances were observed in South Sumatra and East Kalimantan by other researchers (Bompard and Guizol, 1999; Gönner, 1999). Sometimes, the use of fire as a weapon is not so clear-cut. In Sanggau, villagers contesting the rights of a timber plantation to operate within village customary boundaries simply allowed a fire of undetermined origins to burn out of control through fire-prone grasslands along the village border. The fire destroyed an extensive area of the company's newly planted trees, while village farmers effectively protected their own rubber trees.

Forest Degrading Practices

On a number of sites with varied forest types, fire damage was exacerbated by timber harvesting and related land practices, swamp drainage, and repeated deliberate burning as well as accidental escaped fires. Repeated fire reduces options and possibilities for rehabilitating these forests and creates a positive feedback loop whereby forests become more prone to repeat fire damage (Cochrane *et al.*, 1999; Nepstad *et al.*, 1999; Siegert *et al.*, 2001b). In the coastal swamps of Sumatra, the MUBA site provides a good example of unsustainable logging practices and swamp drainage creating an increasingly fire-prone landscape.[10] In 1986, much of the high-density swamp forest (82,741 ha) was part of a logging concession. By 1992, satellite images show that 69,526 ha were already severely degraded swamp forest, 6,898 ha had been drained and converted to transmigration settlements and cultivated fields, and the remainder had been burned but not necessarily converted to other obvious use. The entire remaining forest area (apart from some mangrove) had burned by 1998 (Fig. 4). Similarly, the Long Segar site (Site 8) shows the creation of a drier, more fire-prone landscape since the 1970s with the conversion of closed-cover lowland tropical forest to overlogged and degraded.[11] forest followed by industrial timber plantations, oil palm and other cash crop plantations, or transmigration agriculture (Colfer and Dudley, 1993) (Fig. 6). For Long Segar, the breakdown of the forest cover change estimates between 1983 and 2000, shows the degradation of 44,061 ha[12] of closed-cover lowland forest, all within logging concessions, to secondary forest (20%), fragmented/fire damaged forest (21%) and sparse trees/scrub (45%), the remainder being plantations and agriculture Dennis and Colfer (In press). Repeated fires over an extended history in Sanggau and Tumbang Titi have also led to advanced stages of land degradation characterized by large swathes of fire-prone grasslands (*Imperata*). Similarly, in the Sanggau site, 42% of the 31,552 ha of lowland forest that existed in 1991 had been altered by officially sponsored logging, timber and oil palm plantations, indigenous cultivation, and fire to a mosaic of cultivation and *Imperata* grasslands by 1998 (Fig. 6).

Economic Incentives/Disincentives

The anticipated high profits to both large corporations and smallholders of alternative uses of forest land following logging, in many cases depending on subsequent burning, is a major driving force for deforestation (FWI/GFW, 2002; Holmes, 2000; Tomich and Lewis, 2001; Tomich *et al.*, 1998b, 2001). In seven sites, the transition from logged (both legally and illegally) forests to large corporate, or smallholder plantations is exemplified by the trends we see in Sekincau and Menggala (Fig. 4) and Sanggau and Long Segar (Fig. 6). Although official Indonesian land-conversion policies

[10] Although there is some debate about how "fire-prone" landscapes are formed, for the purposes of this study we use the following definition: a landscape where fires are more likely to occur and spread than they would under previous conditions.
[11] Forest degradation can be defined as a "temporary or permanent deterioration in the density or structure of vegetation cover or its species composition" (Grainger, 1993).
[12] Trajectory of change estimates for only those pixels which are not in cloud in any one of the years.

of the 1990s limited clear-felling of forests for plantation development to already "degraded" forests, policy analysts have long asserted that many timber companies seeking to maximize profits deliberately "degraded" forests within their concessions in order to ensure permission to clear-fell later, or subsequently converting their selective logging concessions to industrial timber or oil palm plantations(Potter and Lee, 1998a,b; Telapak Indonesia, 2000).[13]

Satellite image classifications overlain with maps of plantation concession boundaries also highlighted that not all land where forests had been clear-felled for plantations (much of which was also subsequently burned) was actually planted in plantation crops. In many sites, scrub and grassland or burn scars later covered a very high proportion of the deforested land. For example, in the Menggala peneplains, of the 54,060 ha of forest cleared within designated plantation concession boundaries between 1984 and 1999 only 51% were actual plantations in 1999, 10% was scrub and grassland, 30% was transmigration settlement areas, and 7% appeared as burn scar (Fig. 4). We could perhaps conclude here that the aim in these cases was to obtain the timber with little future interest in developing the land for plantations, as similarly concluded by Potter and Lee (1998a).

Population Growth and Migration

Many areas, in Sumatra and Kalimantan (including extensive areas within the sites of Sekincau, Menggala, MUBA, Tumbang Titi, and Long Segar) were subjected to large-scale government sponsored in-migration associated with Indonesia's Transmigration program (Down to Earth, 2001).[14] Migrants, local land-clearing contractors, and original local customary property, owners intending to turn land over to projects, burned forests and other vegetation to prepare land for new settlements. Such burning was

[13]A Minister of Forestry and Estate Crops decree (No. 376/Kpts-II/1998) on the "Criteria for the Allocation of Forest Land and Oil Palm Estates," according to Potter and Lee (1998) covered the following; "In addition to specifying site criteria for new oil-palm plantations the decree said estates in the forest zone would be steered towards land that was open rather than vegetated, not owned by any party and that was classified as suitable for agriculture in the provincial land use plans." Potter and Lee go on to state "...since the announcement of the decree there has been no evidence that it has operated to limit the spread of oil-palm estates into forested areas."

[14]The original goal of the Transmigration policy was to resettle millions of people from the densely populated islands of Java, Bali, and Madura, to the less densely settled outer islands such as Kalimantan and Sumatra and provide land and new opportunities for the poor migrants. This goal was later superseded by an explicit aim to "develop" the Outer Islands. As described by Barber and Schweithelm (2000) based on the Government of Indonesia Sixth Five-Year Development Plan, "Between 1969 and 1993, the program "opened" 1.7 million ha of agricultural and resettled some 8 million people."

legal prior to 1995, and afterward openly practiced despite official prohibitions. Often migrants, coming mainly from Java and other areas where agricultural burning is not customary practice, were unfamiliar with the precautions traditionally used for small-scale agricultural burning in Sumatra and Kalimantan often resulting in fires escaping into very fire prone environments (Colfer *et al.*, 2000). In other cases, migrants brought their own land use patterns and fire practices with them, which may have involved burning on a smaller scale or at a different time of the year than was appropriate for their new environment, making fire control more difficult. This underlying cause of fire is of moderate importance and is less likely to be an issue in densely populated regions than where rapid inmigration and frontier-style development is under way, with new migrants arriving from distant and dissimilar areas, and forests being cleared for agriculture. In addition, officially sponsored transmigration to Kalimantan and Sumatra has virtually ended, with the exception of resettlement of refugees from disasters and civil violence.

Inadequate Fire Fighting and Management Capacity

Lack of institutional capacity for fire management was apparent in all sites. In many cases, fires deliberately set to assist with land clearing, which burned beyond their intended area into forested areas of commercial or economic value, could not be suppressed due to lack of capacity in terms of management planning for prevention and suppression. This was evident in both natural forests and timber plantations. This situation is less likely to be a major problem in the future as many plantation companies are developing the institutional capacity to manage fire on their concessions—now required under recent national land and forest management reforms. In contrast to large-scale plantation companies, there is a growing body of evidence regarding local capacity to manage fire and prevent its spread among established smallholder communities (Byron, 2004). Moreover, experience from Thailand shows the feasibility of strengthening community level capacity to manage fire (Hoare, 2004). However, institutional capacity is likely to continue to be a major issue in protected areas where the human, financial, and law enforcement resources are not available and customary tenure systems and other local institutions have been disrupted.

Burn Scar Typology

Through the mapping and social interpretation of burn scars in each of the sites patterns of burn scar typology emerge that may also be extended to support a more general typology of fire causes and effects. We found that small regular burn boundaries are often found in areas of smallholder or swidden cultivation; whereas medium–large irregular burns on the periphery of, or just inside corporate plantations suggest areas of conflict between land users, such as in the Menggala peneplains (see Fig. 5, Zone 3, 4, and 5). Regular, large burns within plantation boundaries are most likely to indicate deliberate fires authorised by the plantation company (Fig. 5, Zone 2). We could identify where fires had escaped (accidentally) into plantation areas by the juxtaposition of fire prone areas (e.g., dry swamps) and plantations (Fig. 5, Zones 6 and 1). In swamp areas, large irregular burn scars in open access natural forest areas that had burned during El Niño years were often associated with small-scale natural resource extraction, such as turtle hunting (also described by Jepson *et al.* (1998) and Vayda (1999) in East Kalimantan). Further rigorous testing is required before we can confidently extrapolate beyond the immediate research site boundaries to provide a definitive or predictive link between burn scar typology and cause/perpetrator for Sumatra and Kalimantan. This could provide a powerful policy tool at a wider scale where detailed socioeconomic surveys are not feasible.

DISCUSSION

Research implications focus on the three main outcomes of this research: the methodology it demonstrates, the underlying causes and impacts of vegetation fires, and the policy implications of our findings.

Linking Fire, People, and Pixels

The relationship between remote sensing and social science proved to be extremely positive in this research. Spatial analysis techniques largely answer the questions about what burned and where, at multiple scales of analysis. Linking these analyses with social investigations "on the ground" answered questions about who burned what, as well as why and how people and communities experienced impacts of fire. The remote sensing products provided precise place-specific information on historic and recent patterns of fires and their impacts on vegetation. This provided important guidance to direct and focus social research on the ground that in turn enabled us to draw conclusions about causal processes underlying landscape transformation associated with fire and burning, and understand the human dimensions of the land-cover change seen on remotely sensed imagery. Participatory mapping proved to be a powerful means of linking land-cover classifications based on satellite imagery with information from interviews and narratives provided by people with direct experience of fires. By overlaying the participatory village and landscape land-use maps with the land-cover classifications, we could identify the origins and social significance of the changes so clearly outlined in the remotely sensed imagery. Likewise, the improved explanatory power of combining landscape-scale remote sensing analysis with data obtained through ethnographic and rapid rural assessment methods, along with secondary data sources, impressed researchers initially focusing on the social and institutional dynamics of fire causes and impacts.

Underlying Causes and Policy Implications

The study shows that multiple direct and underlying causes are apparent in each of the eight sites. Important findings include the indication that fire causes at each site differ widely and are complex and diverse, and the lack of a clearly dominant single cause of fire at any of the sites. This complexity is understandable within the context of multiple stakeholders and land-use activities on the sites. The results strongly indicate that effective approaches to preventing and managing fire, and to solving, or lessening fire problems must be multifaceted, and must target specifics of complex fire causes in particular regions and localities (Tomich and Lewis, 2002).

We believe that complex sets of causes underlying recent serious fires probably characterize fire problems in most parts of western Indonesia. Potter and Lee (1998a) arrive at a similar conclusion in their study of the oil palm plantations: "...in each case quite complicated, with a number of active participants involved and contributing to the burning." Similarly, in a comparative study of the proximate and underlying driving forces of deforestation, Geist and Lambin (2002) found many and varied causal factors revealing no single dominant cause–effect pattern.

Although the results of this study do not belittle the importance of macrostructural causes of Indonesia's recent fire crises, they do contradict assertions that originate from a wide range of political standpoints insisting that solutions will be found almost entirely in national policy reforms broadly aimed at structures of centralized land allocation, developmentalist regional investment policies, inequitable imperatives toward global commodity exports, cronyism, and corruption. They also belie the research-related corollary of such assertions: that detailed research on specific causes and impacts of particular fires is not necessary or is superfluous, from a policy perspective, and that such particular research may actually serve to obscure the most significant fire causes and reduce pressure for necessary structural reforms (compare Byron, 2004; Gellert, 1998).

Based on the identification of both direct and indirect causes and impacts of fire in this research, we have outlined some policy issues and implications of this research for the regions studied, and by extension for Indonesia. The policy implications we note in the following analyses highlight the value of the hybrid methods developed in this study. Two crucial sets of policy issues relate to (a) the need to reduce the use of fire as a tool in land clearing, and to reduce fire risks where burning continues; and (b) the need to resolve problems relating to land-use allocations and tenure, which result in widespread uncontrolled fires. Additional policy reforms and their effective implementation are required to reduce forest degrading practices and population pressures that result in increased burning, and to build economic incentives and disincentives as well as legal, administrative, and other institutional capacity to promote more sustainable uses of land and management of fire.

Reducing the Use of Fire as a Land-Clearing Tool, and Reducing Risks Where Fire Burning Continues

The central government's current official zero-burning policy, if effectively enforced by Provincial governments, could directly reduce the fire problem. However, many land development and plantation companies claim that preparing land for plantation crops without burning, while technically feasible, remains impractical and uncompetitive under Indonesia's current structure of fiscal incentives and lack of meaningful penalties for illegal burning (Simorangkir and Sumatri, 2002). Conversely, the expansion and expectations of reasonable profits by several oil palm and timber plantations by companies in Indonesia and Malaysia that have consistently used zero-burn techniques calls such assertions into question (Guyon and Simorangkir, 2002; Simorangkir *et al.*, 2002).[15]

Some policy analysts suggest that some land clearing with fire should be allowed, under limited, relatively low-risk conditions, and only with appropriate safeguards (Byron, 2004; Tomich and Lewis, 2002). To implement

[15]These include companies operating in or adjacent to study sites for this research—Finnantara Intiga timber plantation in Sanggau, and the Golden Hope oil palm plantation near Tumbang Titi in Ketapang. Golden Hope's "no burn" practices have guided the standard now required by law in Malaysia. Simorangkir *et al.* (2003) conclude "Generally zero-burning methods are not more expensive than burning, especially when replanting oil palms or rubber trees, or clearing low secondary vegetation or heavily logged-over forests. Burning is more economical for clearing high-volume forest . . . In the long term . . . zero burning will actually be more cost effective mainly due to lower fertilization costs, pay off of fire management system, and lower socioeconomic costs of fire damages" (p. 34).

such a policy, practical and accurate early warning mechanisms for high-fire risk conditions would be required for land managers to make prudent decisions about when, where, and how to burn, and to prepare appropriate and sufficient workforce, expertise, equipment and infrastructure to suppress escaped fires. In addition, more research is needed into alternative methods of land preparation and management that either require no burning or generate less smoke (Murdiyarso *et al.*, 2004). This is especially pressing with regard to developing peat lands and other wetlands, where fires have tended to spread very widely and rapidly, and generate the bulk of the smoke that has prompted such great concern among Indonesia's neighbors and those concerned about global carbon loadings (Page *et al.*, 2002; Tacconi, 2003; Tan and Tay, 2003; Tomich and Lewis, 2002). Under current political and administrative conditions, any of these policy directions will demand considerable investments in both institutional and technical capacity by Indonesia's central and regional governments, international assistance, in addition to new private investments.

Land Tenure, Land Use and Resource Allocation, and Regional Autonomy

Evidence from our research confirmed that by far the most common underlying cause of fire was related to competition and conflict about land tenure and land allocation.

Early hopes in the post-Suharto reform period that increased regional administrative and fiscal autonomy would enable the equitable and effective reforms in resource allocation necessary to reduce fire risks originating in tenure conflicts or uncertainty (Barber and Schweithelm, 2000; Down to Earth, 2002) are now being put to the test, with less than encouraging indications to date. Prior to 1999, when the reforms started to come in to effect,[16] central government agencies granted resource-use concessions to private companies, parastatal enterprises, and government land development projects. Land-use allocation decisions made by central government agencies frequently overlaid concession and project boundaries on local jurisdictions and indigenous communities' customary territories, and property held under local customary law (*adat*). In some cases, different central government agencies designated incompatible uses on the same land (most seriously, mining or logging concessions in nature conservation areas).

Regional reform clearly opens the way for resolution of resource conflicts in ways more in keeping with the diversity of local customary law,

[16]The most significant regional autonomy laws are Law 22 on Regional Governance and Law 25 on Fiscal Balancing, both issued in May 1999 (Resosudarmo and Dermawan, 2002). Official national decentralization began on 1 January 2001.

and offers opportunities for regional government to "harmonize" decisions with those of local and customary institutions. From a recent CIFOR study of decentralisation and forests across Kalimantan and Sumatra, evidence of stakeholder participation and consultation in district decision-making was variable. For example, Casson found positive evidence in West Kutai District, East Kalimantan, especially the involvement of local NGOs. However, the scenario in Central Kalimantan was much more disheartening (Casson, 2001a,b). Ironically in Kalimantan and Sumatra, the regional authorities' increased access to and dependence on regionally generated revenues may actually increase pressure on officials to permit potentially lucrative uses of land and resources claimed by local communities and their members, regardless of their effects on fire risks (Barr *et al.*, 2001). Strong regional institutions, representing local interests through elected representatives and consultation with people most directly affected by resource allocation decisions, as well as with commercial and other stakeholders, must give significant weight to local interests in social justice in the face of often overwhelming commercial pressures (Bennett, 2002; Byron, 2004; Tomich and Lewis, 2002).

Regional reforms should also ensure that land and resource allocations and decisions at all levels are compatible with physical site characteristics, prominently taking fire risks into account. Technical aspects of these analyses should be widely accessible, and should assess a wide variety of potential impacts of proposed developments—including fire risks—as well as opportunities for more sustainable alternative land and resource uses. However, Indonesia's legacy of inaccurate maps, overlapping boundaries, and a lack of technical expertise at the Provincial and District levels will make this a difficult task (Potter and Badcock, 2001).

Reducing Forest Degrading Practices

Policies to improve land management by all stakeholders, and measures to restore ecological integrity to degraded natural forests are extremely important to reduce the incidence of repeated fires in the remaining logged-over and secondary forests of Kalimantan and Sumatra. Promoting community involvement in such rehabilitation efforts or management plans is critical for their success in reducing fire risks. Sustainable land use by smallholders integrating both subsistence crops (including diverse rice and other staple cultivation systems) and commercial crops (focusing on sustainable and lucrative agroforestry production with potential regional comparative advantages, such as rubber, coffee, fruit, rattan) needs to be promoted through improved government support for research and extension services, along with opportunities to enlist the resources of private enterprises.

Our research (e.g., at Menggala, MUBA, and Tumbang Titi) strongly indicates that special attention should be paid to swamp areas, where risks of extensive fires have been extremely high; and deforested landscapes, which in drought years are very fire-prone. Regional authorities should approve land development proposals only with the strongest precautions to reduce risks generating smoke and uncontrolled fires. The need to sustain existing transmigration schemes in the face of limitations on burning and high risks of wildfire calls for technical assistance and appropriate resources to these new communities.

Developing locally acceptable techniques and institutional mechanisms to rehabilitate fire-prone *Imperata* grassland and other fire-degraded vegetation for more economically (and in many cases more ecologically) productive and fire resistant use holds promise for reducing the future incidence and impacts of devastating fires (Garrity, 1996/97; Menz *et al.*, 1998; YDT, 2003). Such efforts could generate significant and sustainable income for local people as well as large-scale industry, unlike Indonesia's dominant models of industrial timber plantations and authoritarian "regreening" programs. Evidence from both failed and successful programs to date suggests that reinforcing local stakes in effective rehabilitation will be important (Hartanto *et al.*, 2003).

Building Institutional Capacity to Prevent and Suppress Fires

In Indonesia, as elsewhere, efforts to improve fire management have confronted tension between focusing resources on fire prevention versus fire suppression, and choices between building fire management systems based on centralized, authoritarian/paramilitary models versus more decentralized, participatory, consultative, community-based models (Moore *et al.*, 2002). Recent legal and administrative reforms require companies to control fires within their concession areas and private holdings (ostensibly requiring them to invest in fire suppression) and monitor or control burning by smallholders within their boundaries. Regional governments at Provincial and District levels are scrambling to implement new fire management policies, designate responsibilities, and provide appropriate staff and technology. The effectiveness of these measures has not yet been tested.

The results of this study suggest two major considerations in building institutional infrastructure for fire management. First, the diversity of underlying causes of fire and of fire impacts in Kalimantan and Sumatra highlights the need to develop fire management systems that address particular concerns of specific areas. A national framework providing some uniformity of purpose should help make available appropriate and sufficient resources to improve fire management to regions that need them, while recognizing the diverse needs of different regions and the people within them.

Second, remote sensing technology, digital mapping, and instantaneous communications hold great promise for supporting Indonesian efforts to predict, detect, and respond to potential fire crises, and eventually to prevent unwanted fires from occurring (Tomich, 1999). These technologies also hold promise for supporting enforcement of burn prohibitions and investigations of alleged illegal commercial burning. However, "high-tech" information and communication must be broadly accessible, widely used, and transparently controlled if they are significantly to improve fire management "on the ground" in remote regions. Institutional capacity to deploy "high tech" information technology cannot replace locally based knowledge, skills, planning and cooperation, a sense of fairness, and material resources for fire management.

Economic Incentives and Disincentives

Beyond providing effective criminal and monetary penalties for illegal burning and liability for fire damage, some policy analysts seeking solutions to Indonesia's fire problem place enormous confidence in the potential for economic policy reforms and market-based incentives to minimize fire risks and promote sustainable land use, with disincentives for forest conversion and unsustainable land use. Although the rationales behind many proposed policy instruments are clear in economic theory, serious empirical tests for most of them must wait for their large-scale implementation.

A combination of eco-labeling and international trade restrictions to shrink markets for commodities produced in ways that pose high-fire risks may hold promise. For example, "fire-safe" labeling programs, similar to emerging eco-labeling of sustainable timber or shade-grown coffee, could identify products grown by companies that do not burn, and by members of communities that have adopted effective measures to minimize risks of accidental fire. Over time, international restrictions could limit trade in products whose producers cannot demonstrate that their products originate in legal production areas.

Providing fiscal advantages to support companies' initial investments in more effective fire management above and beyond increased legally required minimum levels could make such over-minimum investments more appealing to timber, plantation, and mining companies. However, with ongoing fiscal devolution to regional governments, such measures would likely require support from central government or international sources.

Other market-oriented measures could include the removal of marketing restrictions on wood from agroforestry species felled during replanting (e.g., eliminating marketing restrictions on rubber wood), which would reduce biomass burning and hence smoke pollution (Tomich and Lewis, 2001). However, such incentives would need to be carefully crafted to cover only planted agroforestry species and to avoid encouraging additional deforestation.

CONCLUSION

As outlines of Indonesia's national and regional fire management institutions are just emerging, debates on the most effective means to build fire management capacity are colored by broadly contested debates on political, economic, and administrative reform. All agree that more effective fire management must draw on technical knowledge and investments by government at several levels, land development and resource extraction companies, and local smallholders and communities. However, these parties often disagree about the most effective division of responsibilities, and about the fair share of total efforts that each should bear.

This study identifies both constraints on institutional development for fire management, and specific opportunities to improve fire management within each region studied, and in general. The diversity and complexity of underlying fire causes that this study identifies also point to three areas of controversy where study results suggest appropriate opportunities.

The first relates to the appropriate balance between programmatic fire management efforts addressed toward large companies and toward smallholders, whose activities each pose fire risks. Some critics representing communities of indigenous farmers and forest users resent a disproportionate focus of regional fire management programs and campaigns toward activities by smallholders, whose swidden cultivation and agroforestry they believe pose less overall fire risk than large-scale industrial land clearing in adjacent areas. On the other side, industry representatives, especially from companies that consider themselves responsible actors, resent being demonized by general assertions that commercial land clearing is the major culprit in Indonesia's fire crisis. They call for more government technical and financial assistance to help them reduce fire risks while maintaining their competitive low costs. "Hybrid" methods such as those used in this research can help identify an appropriate, equitable, and cost-effective mix of program targets in particular areas, assessing relative risks posed by various parties based on area-specific evaluation of past fire events and plans or expectations for future development (Simorangkir *et al.*, 2002).

The second area of controversy where study results suggest opportunities to improve fire management relates to finding an appropriate balance in efforts and resources to improve fire management undertaken by government agencies, companies, and communities in fire-prone areas. Government-sponsored programs should promote, and in some cases require, company investment in fire management, including planning, appropriate training, and equipment purchases according to assessments of regional risks, along with evaluation of existing capacities.

Through methods like those developed in this research, graphic and narrative evidence of past fire damage and continuing risks in specific areas would provide government agencies, communities, and logging or land development companies with information they could use to work together to reduce risks from logging or land-clearing practices, flammable logging debris, and fuel loads and fire susceptibility in residual forests and plantations. For example, graphics like the overlay maps produced in this research could help identify areas where all could benefit from collaboration between companies and adjacent communities to protect common or adjacent resources. Such measures might even help reduce long-standing animosities stemming from resource access and overlapping boundary conflicts. Such maps could also point out areas where company equipment and infrastructure could help reduce fire risks along and within community boundaries, and places where companies could most effectively protect their assets from fire by hiring, training, and supplying fire protection teams of local community residents. In addition, we recommend that policymakers and those interested in improving fire management actually read the relevant case studies.

These approaches could also prove vital in eliciting community participation in fire management at all levels and in all forest types and agro-ecosystems, particularly in protected areas where government and company resources for forest protection may be especially limited, given the lack of government revenue and direct legal income from these forests. Widespread public information and targeted education to build awareness regarding fire prevention, suppression, and management is crucial. Locally adapted information about specific areas' fire histories and future risks, as well as broader regional analyses, could help mobilize local support from all parties to improve fire management, through independent or collaborative efforts.

A third area where the approach developed in this study offers some suggestions concerns developing institutional capacity for fire management with scarce government resources, to upgrade programs in a context of devolution of responsibilities for fire management. Under regional autonomy reforms, responsibility for fire management, including planning, suppression, and prevention, has devolved almost entirely from two Ministries in Jakarta to regional authorities at Provincial and District levels.

In Kalimantan and Sumatra, facing the array of pressing new demands on their limited resources the regional authorities have given investment in staff, training, equipment, legislation, and law enforcement for fire management relatively low priority. The methods developed in this research could be especially useful in supporting strategic planning for regional fire management by helping to identify high fire-risk areas and the underlying reasons for risk that fire prevention planning must address in particular places. They could also help in developing regional strategies to organize human resources, equipment, and infrastructure for fire suppression.

Few regional officials have been willing to enforce the centrally mandated burn ban, in part due to their recognition that it would be political suicide, as well as adversely affecting smallholders dependent on burning for survival, and in part due to the burden of assembling sufficient evidence to support legal prosecution. Based on a limited number of recent court cases to prosecute alleged illegal burning, it appears that both criminal responsibility and civil liability have been difficult to prove.[17] The methods developed in this research could support law enforcement efforts by providing models that combine evidence from multiple types of sources, where remote sensing analysis can corroborate narrative evidence of fire witnesses, or victims of property destruction.

The catastrophic fires that burned millions of hectares of forest and farmland throughout Indonesia during the past two decades have left an indelible mark on the physical, cultural and political landscape. The threat of future catastrophic fires looms large, as many of the underlying causes of fire identified in this study remain prevalent or exacerbated, and added to this is the certain return of El Niño induced drought conditions. Developing effective approaches to decrease the impact of future fire catastrophes will test both governance and the potential of cross-disciplinary science in a world increasingly aware of global interests in local and regional resource management decisions.

[17] After repeated failures in prosecuting cases of illegal burning despite presentation of strong evidence, the conviction of the General Manager of P.T. Adei Plantation for illegal burning in 1999 in Riau (the original decision in 2001, upheld by Indonesia's Supreme Court in late 2002) provided guidance for the preparation of evidence in future cases. Combined sources of evidence, including narrative accounts, physical evidence on the ground, and remote sensing analyses as demonstrated by Judicial Team (Tim Yustisi) examples in West Kalimantan, could be developed along the lines of the case studies in this research (Project FireFight South East Asia (2003) and information provided to Judith Mayer by Ir. Wawan Hermawan, Kepala Bidang Pengendalian Pencemaran dan Kerusakan Lingkungan, BAPEDALDA Kalimantan Barat, June 2003).

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