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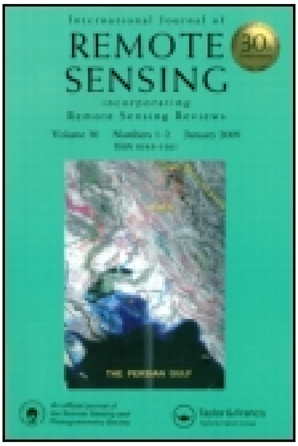

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REVIEW ARTICLE

Detection of vegetation fires and burnt areas by remote sensing in insular Southeast Asian conditions: current status of knowledge and future challenges

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The humid tropical insular Southeast Asian region is one of the most biologically diverse areas in the world. It contains around 70 Gt of carbon stored in peat deposits susceptible to burning when drained and it has significantly higher population density than any other humid tropical region. This region experiences yearly fire activity of anthropogenic origin with widely varying extent and severity. At the same time, there are several geographic, climatic, and social aspects that complicate fire monitoring in the region. In this review article, we analyse the current knowledge and limitations of active fire detection and burnt area mapping in insular Southeast Asia, highlighting the special characteristics of the region that affect all types of remote-sensing-based regional-level fire monitoring. We conclude that the monitoring methods currently employed have serious limitations that directly affect the reliability of results for fire and burnt area monitoring in this region. With the materials and methods presently available, the regional and global effects of fire activity taking place in insular Southeast Asia are in danger of being underestimated. New approaches utilizing higher spatial and temporal resolution remote-sensing data are needed for more detailed quantification of fire activity and subsequently improved estimation of the effects of fires in this region.

1. Introduction

Over the past decade, vegetation fires have affected around 4 million km^2 worldwide annually (Tansey et al. 2008b), causing close to 2 Gt of yearly carbon emissions into the atmosphere (van der Werf et al. 2010). The great majority of biomass burning takes place in the tropical regions (Giglio, Csiszar, and Justice 2006a; van der Werf et al. 2010). Current fire frequency in the tropics is extraordinarily high in the long-term historical perspective, mainly on account of anthropogenic biomass burning (Bird and Cali 1998; Goldammer 2006). Fire is widely used in land management, hunting and pest control, or sometimes even as a weapon in land tenure conflicts (Andreae 1991; Qadri 2001; Stolle et al. 2003; Suyanto 2006). In addition, negligence (e.g. cigarette stumps) may lead to accidental ignition of vegetation fires, a risk that is exacerbated by high population density. Furthermore, both prescribed burns and accidentally ignited fires can easily spread in dry conditions and develop into uncontrolled wildfires.

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The effects of fires vary significantly across the tropical regions depending on how well the local ecosystems have adapted to fire. Fires taking place in the humid tropics, where fire in natural conditions is rare, can have serious long-term consequences (Sanford et al. 1985; Goldammer 1999, 2006). Total or partial destruction of vegetation cover by fire affects species composition, vegetation structure, and nutrient flux in a variety of ways (Dwyer et al. 1999). Furthermore, fires cause a wide range of secondary effects including local human health problems, economic losses, and emissions of trace gases and aerosol particles that play important roles in atmospheric chemistry (Crutzen and Andreae 1990; Levine 1999; Qadri 2001; Heil, Langmann, and Aldrian 2006; Hyer and Chew 2010). Biomass burning has been estimated to produce up to 40% of annual anthropogenic carbon emissions in severe fire years, thereby contributing considerably to the rising CO_2 concentration in the atmosphere (Levine 1996; Page et al. 2002; Cochrane 2003; van der Werf et al. 2010).

Regional- to global-level monitoring of vegetation fire activity is needed to quantify the extent of biomass burning and thereby enable improved modelling of the consequences of fires such as ecosystem destruction and human health problems, as well as both direct contributions and feedback to global climate change. Two fundamentally different approaches can be used to estimate the occurrence and effects of fires: active fire detection and burnt area mapping. Active fire detection (i.e. hotspot detection) is based on the detection of the thermal infrared radiation (TIR) emitted by fires. Hotspot detection can be effectively used to determine the seasonality, timing, and interannual variation of fires (Eva and Lambin 1998a; Stolle et al. 2004). However, owing to the polar-orbiting tracks of most satellites used in active fire detection, the results may have serious bias caused by the combination of regional burning practices and fixed overpass times of the satellites (Eva and Lambin 2000; Hyer et al. 2013; Reid et al. 2013). Furthermore, cloud cover effectively prohibits active fire detection, which can be especially harmful for fire-monitoring efforts in humid tropical regions such as insular Southeast Asia.

Active fire detection cannot be used directly to map the extent of the burnt area, which limits its usability in quantifying the consequences of biomass burning. Sensors used for active fire detection have widely varying spatial resolutions, ranging typically from around 1 km^2 for polar-orbiting satellites to dozens of square kilometres for some geostationary satellites. However, the sensors are sensitive to fires of much smaller size: a pixel of 1 km^2 in size can be saturated by a fire leaving behind a 0.001 km^2 burn scar. Despite these limitations, due to the great need for information on the effects of vegetation fires and the lack of more reliable methods, active fire detection has been tested for estimation of the extent of burnt area both globally (e.g. Giglio et al. 2006b, 2009) and at the regional level in different parts of the world (e.g. Eva and Lambin 1998a; Stolle et al. 2004; Miettinen, Langner, and Siegert 2007). But these studies have produced widely divergent estimates.

Burnt area mapping aims at detecting and delineating burn scars using the spectral signature of the post-fire landscape and/or the spectral changes from pre-fire to post-fire conditions. In theory, burnt area mapping can be used to derive the extent and spatial distribution of burn scars. This information can further be used in conjunction with other data (e.g. pre-fire land-cover maps, soil/peat maps, and biomass information) to estimate the effects of the fires. During the last 15 years, large-scale burnt area mapping has been extensively studied using coarse- ($\geq$1 km^2) and medium-resolution (250–500 m) sensors (Barbosa, Pereira, and Grégoire 1998; Eva and Lambin 1998b; Roy et al. 1999; Roy, Lewis, and Justice 2002; Roy et al. 2005; Martín et al. 2002; Nielsen, Mbow, and Kane 2002; Stroppiana et al. 2002; Stroppiana, Grégoire, and Pereira 2003; Pereira 2003; Sá et al. 2003; Silva et al. 2004; Chuvieco et al. 2005; Loboda, O'Neal, and Csiszar 2007; Tansey et al. 2008b; Veraverbeke, Harris, and Hook 2011). Many of these studies have been aimed at the creation of regional or global burnt area mapping methodology. However, it has been shown that the extent of burnt area derived using different burnt area detection algorithms may vary considerably (Boschetti et al. 2004). Furthermore, the most promising results from the above-mentioned studies have been achieved in ecosystems with vegetation and climate conditions differing greatly from the conditions of insular Southeast Asia. Few studies (Fuller and Fulk 2001; Miettinen 2007; Miettinen and Liew 2008, 2009) have investigated the potential of burnt area mapping, particularly in insular Southeast Asia, and those studies have identified serious limitations in the currently available materials and methodologies.

In this review article, we analyse the current knowledge and limitations of active fire detection and burnt area mapping in the humid tropical insular Southeast Asian region. This region has several unique characteristics that make fire monitoring particularly challenging. At the same time, this region is one of the most biologically diverse areas in the world, including unique ecosystems and animal species (Whitmore 1984; Corlett 2009); it contains up to 70 Gt of carbon stored in vast peatlands susceptible to burning when drained (Page, Rieley, and Banks 2011) and it has significantly higher population density than any other humid tropical region in the world. These characteristics exacerbate the effects of vegetation fires and emphasize the importance of and urgent need for improved quantification of fire activity taking place in this region.

2. Characteristics of fire activity in insular Southeast Asia

2.1. Geography and climate

In general, insular Southeast Asia refers to the archipelagic part of Southeast Asia. It is also often called the Maritime Continent. In this article, we concentrate particularly on the equatorial humid tropical parts of the region, limiting our focus to an area between 10° S and 10° N, covering the Malay Peninsula and the islands between 95° E and 140° E (Figure 1). This area is divided between six countries: Brunei, East Timor, Indonesia, Malaysia, the Philippines, and Singapore. Major islands in this area include Sumatra, Borneo, Java,

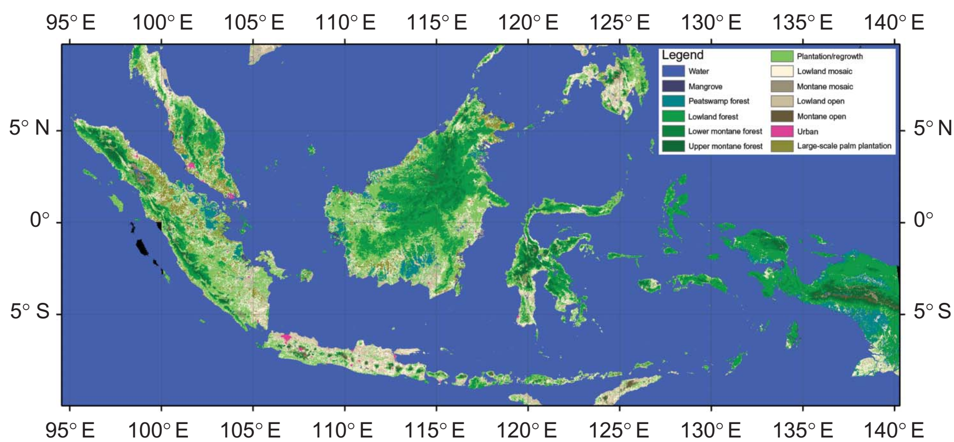

Figure 1. Area of interest for this review article. Note the high variability of land-cover types, particularly in the western half of the region where the majority of the fire activity has taken place over the past two decades. Land cover map by Miettinen et al. (2012). Map available at: http://www.eorc.jaxa.jp/SAFE/LC_MAP/

Sulawesi, and the western part of New Guinea. Fire activity is heavily concentrated in the islands of Sumatra and Borneo, which included nearly 70% of all active fires detected between 2000 and 2009 in the entire region (Reid et al. 2013).

The climate of insular Southeast Asia is among the most consistently humid tropical climates in the world. In general, the weather is hot and humid all year round, with a drier period of 2–3 months that in most parts of the region occurs between June and November. The majority of the fire activity takes place during this drier period. On average, 77% of fires in the region took place between July and November in 2000–2009 (Reid et al. 2013). Even during the drier periods, rainfall exceeds evaporation in many parts of the region (Whitmore 1984). High humidity levels are also connected with persistent cloud cover, which is particularly harmful for optical remote sensing.

Insular Southeast Asia is known for its lush tropical evergreen forests and has the highest biodiversity of all tropical regions of the world (Whitmore 1984; Corlett 2009). Natural vegetation varies from tall lowland forests dominated by dipterocarps and low heath forests on poor soils to various types of montane and wetland vegetation. Perhaps the most singular and highly significant feature for fire monitoring in this region is the vast extent of peatlands. Around 250,000 km^2, or nearly 60% of global tropical peatlands, can be found in insular Southeast Asia (Page, Rieley, and Banks 2011). These peat deposits, which can be 20 m deep, not only support unique peat swamp forest ecosystems, but are estimated to contain around 70 Gt of carbon (Corlett 2009; Page, Rieley, and Banks 2011). Peatlands can be found mainly in the coastal lowlands of Sumatra, Borneo, and New Guinea Islands. Nowadays the majority of the natural vegetation in the region has either been converted to agroecosystems or degraded while deforestation and land-cover change continues to take place at a high rate (Fuller, Jessup, and Salim 2004; Kauppi et al. 2006; Langner, Miettinen, and Siegert 2007; Miettinen, Shi, and Liew 2011b).

2.2. Fire occurrence in insular Southeast Asia

Undisturbed humid tropical forests are very resistant to fire (Uhl, Kaufman, and Cummings 1988; Uhl and Kaufmann 1990; Cochrane and Schulze 1999). Rare fires may take place during extraordinarily dry periods, but they typically occur in the form of small surface fires (Sanford et al. 1985; Goldammer 2006). Human activities make humid tropical forests more vulnerable to fire by opening the canopy, accelerating the drying process, and increasing the amount of dry fuel (Cochrane 2003). This not only increases the risk of fire but also causes fires to become more severe and destructive (Siegert et al. 2001). The first documentation of vegetation fires in Southeast Asia dates back to the late nineteenth century (Goldammer 2006). Over the twentieth century, the use of fire in land management increased gradually before escalating rapidly since the 1980s. Two unprecedented regional-level fire events took place in the late twentieth century (1982–1983 and 1997–1998) coinciding with strong El Niño conditions. The extent and disastrous consequences of these fire events have been blamed largely on the degradation and conversion of natural ecosystems (Goldammer 2006).

Fire is an integral part of the rapid land-cover change that has been taking place in insular Southeast Asia for the past 30 years. Fire is extensively used as a tool in land clearance and agricultural field preparation by both smallholder farmers and plantation companies (Ketterings et al. 1999; Bowen et al. 2001; Chokkalingam et al. 2006; Simorangkin 2006). Deliberate land management burning frequently spreads outside its intended borders and develops into uncontrolled wildfires (Bowen et al. 2001; Goldammer 2006). Intentional and unintentional burning has become an annual problem, especially in drained peatlands, occasionally resulting in catastrophic fire episodes releasing large amounts of carbon into the atmosphere (e.g. Page et al. 2002; Heil, Langmann, and Aldrian 2006; Field, van der Werf, and Shen 2009; van der Werf et al. 2010). Fire is still considered to be the cheapest, and most of all the simplest, way to carry out land clearance and preparation in peatland areas due to both its pest-controlling effects and the difficult working conditions for heavy machinery in peat swamp forests (Simorangkin 2006).

Numerous authors have investigated the variation in fire regimes and the underlying causes of fires from a social and political perspective, emphasizing the influence of land management policies on fire activity in this region (e.g. Ketterings et al. 1999; Bowen et al. 2001; Stolle et al. 2003; Dennis et al. 2005; Chokkalingam et al. 2006; Murdiyarso and Adiningsih 2006). The effects of physical constraints on fire regimes have been less studied, but the results indicate that intra- and inter-annual variations in regional climate affect fire severity considerably and that fire regimes vary between land cover and soil types (van der Werf et al. 2008, 2010; Field, van der Werf, and Shen 2009; Langner and Siegert 2009; Miettinen, Shi, and Liew 2011a; Reid et al. 2013).

2.3. Implications of the characteristics of the region on active fire and burnt area monitoring

When taken together, the above-mentioned characteristics of climate, geography, and fire occurrence in insular Southeast Asia create unique and complicated conditions for active fire and burnt area monitoring. First, high humidity levels result in strong cloud formation that radically restricts the usability of optical remote-sensing methods. In theory, cloud cover is less disruptive to burnt area mapping than to active fire detection (due to fire scars that persist for several weeks). Nevertheless, persistent cloud cover complicates burnt area mapping as well, by lengthening the intervals between monitoring and causing a wide variety of cloud-related artefacts in remote-sensing datasets.

The variety of ecosystems and land-cover types in the region is broad, ranging from pristine evergreen broadleaf forests, forests degraded to varying degrees, 'man-made' savannas, and vast drained degraded peatland areas to large-scale plantations and small-holder agriculture. The predominantly anthropogenic origin of fires in combination with the varying land cover and soil characteristics results in highly varying types of individual fires (Nicolas 1998; Bowen et al. 2001; Miettinen and Liew 2004, 2009). The fact that this region has a wide selection of land-cover types and fire regimes, and thereby also a wide selection of varying fire-induced spectral changes, means that the accuracy of active fire and burnt area monitoring using methods developed outside insular Southeast Asia may vary greatly within the region and over time, leading to mixed and unpredictable reliability of the results on the occurrence and effects of vegetation fires in the region.

Fire activity in this region can be coarsely grouped into three different categories: (1) smallholder land-preparation fires, (2) large-scale land conversion fires, and (3) wild-fires (Figure 2). Smallholder land-preparation fires are used to clear new agricultural fields (e.g. in shifting cultivation) or merely prepare fields or pasture land for a new season by burning the remnants of the previous crop. These fires are short lived and the geometrically shaped small burn scars left behind are usually less than 0.25 km^2 in size (Nicolas 1998; Bowen et al. 2001; Miettinen and Liew 2004). Large-scale land conversion, on the other hand, is typically undertaken by plantation companies aiming to establish new plantation areas. These fires burn over several days and nights, leaving behind extensive geometrically shaped burnt areas (Figure 2). Wildfires may burn continuously for weeks and result in large, irregularly shaped burnt areas commonly in excess of tens of square

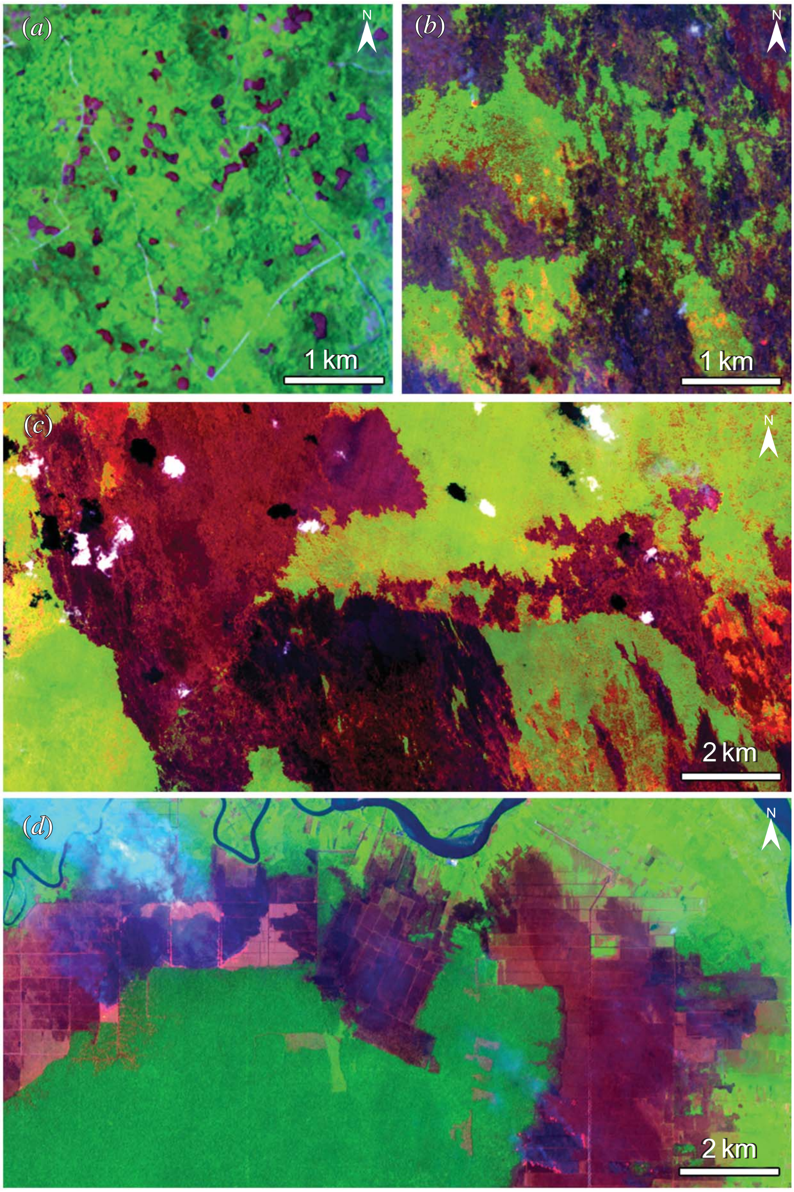

Figure 2. Illustration of the three main categories of fire activity in insular Southeast Asia as seen on SPOT 4 and 5 high-resolution (10–20 m) images: (1) smallholder land-preparation fires (*a*), (2) large-scale land-conversion fires (*d*), and (3) wildfires (*b*) and (*c*). Figure taken from Miettinen and Liew (2009). (RGB: 432) (SPOT image © 2006 CNES).

kilometres (Nicolas 1998; Bowen et al. 2001). Long-lasting wildfires are particularly common in peatland areas where they progress slowly, burning within the peat layers. They may burn without visible flame but produce thick smoke spreading widely over the region. Altogether, these three types of fire form the basis of biomass burning in insular Southeast Asia. All three types take place annually, but their intensity and proportions vary between years (Liew et al. 2005b; Chia et al. 2007; Liew, Chia, and Kwoh 2007; Chew et al. 2008; Langner and Siegert 2009; Shi, Miettinen, and Liew 2010; Miettinen, Shi, and Liew 2011a; Reid et al. 2013).

3. Active fire detection in insular Southeast Asian conditions

3.1. Coarse-resolution satellites

Active fire detection by satellites is based on the use of thermal sensors to record the heat emitted by fires. The amount of thermal radiation emitted at a particular wavelength from a warm object depends on its temperature. If the Earth's surface is regarded as a black body emitter, its apparent temperature (known as the brightness temperature) and spectral radiance are related by Planck's law (Rybicki and Lightman 1979). For a surface at a brightness temperature of around 300 K (roughly corresponding to the surface temperature of the Earth), spectral radiance peaks at a wavelength around 10 μm. Following Wien's displacement law, peak wavelength decreases as brightness temperature increases (Rybicki and Lightman 1979). For typical fire temperatures from about 500 K (smouldering fire) to over 1000 K (flaming fire), peak radiance occurs at around 3.8 μm, which coincides with band wavelengths of several coarse-resolution satellites including, for example, the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) and the Moderate Resolution Imaging Spectroradiometer (MODIS). Active fire detection algorithms generally also use one or more bands at longer wavelengths (10–12 μm) to eliminate false alarms.

Active fire detection algorithms have been developed since the 1980s mainly utilizing the NOAA AVHRR sensor, and hotspot detection has been applied in numerous projects (Dozier 1981; Matson, Stephens, and Robinson 1987; Robinson 1991; Kaufman and Tucker 1990; Setzer and Malingreau 1996; Rauste et al. 1997; Christopher et al. 1998; Pereira 1999). It is only more recently, however, that standardized and consistently produced active fire products have been made publicly available. For insular Southeast Asia, the Along Track Scanning Radiometer (ATSR) night-time fire product has had the longest lifespan, having been introduced in 1996 (ATSR website). The most advanced and widely used sensor for active fire detection is the MODIS sensor on board the Terra and Aqua satellites. The MODIS bands are specifically designed for fire monitoring and the active fire detection products have been available since 2000 (Kaufman et al. 1998; Justice et al. 2002; Giglio et al. 2003). The MODIS sensor saturates at higher temperatures than other sensors commonly used for active fire detection (450 and 400 K for the 3.7 and 11 μm bands, respectively), which improves fire detection accuracy. Another advantage of the two MODIS instruments is that they provide four daily observations (two daytime and two night-time passes) over most locations in the tropics. MODIS active fire detection has been widely used in insular Southeast Asia, not only for monitoring fire activity but also for assessing the extent of burnt areas (e.g. Langner and Siegert 2009; Miettinen, Shi, and Liew 2011a).

Although publicly available global active fire products are useful for analysing the general distribution and interannual variation of fires within the region, the global nature of the detection algorithms may decrease detection accuracy in climatologically and geographically unique areas like insular Southeast Asia. Accuracy assessments of global active fire products conducted in this region have not only indicated high commission and omission error levels (~30%), but also highlighted remarkable differences in the quantity and type of fires detected by different active fire products (Liew et al. 2003; Stolle et al. 2004). In order to improve fire detection accuracy, locally developed algorithms can use climatology or other local data to constrain the non-burning background, this tighter constraint permitting better detection of marginal fires than could not be captured by a global product without significantly increasing false-positives. In insular Southeast Asia, at least three local active fire detection approaches utilizing knowledge of local ground conditions, fire type, and varying atmospheric humidity levels have been developed (Nakayama et al. 1999; Fuller and Fulk 2000; Liew, Lim, and Kwoh 2005a). Both Nakayama et al. (1999) and Liew, Lim, and Kwoh (2005a) reported slightly better detection accuracy than the standard global algorithms, while Fuller and Fulk (2000) did not compare their results to any globally used algorithm.

Locally tuned algorithms can improve detection accuracy, but temporal sampling remains a problematic issue with all the polar-orbiting satellites introduced above. MODIS and AVHRR together can provide as many as 10 daily overpasses for the insular Southeast Asian region, but even then some gaps in temporal coverage remain during important parts of the fire diurnal cycle, especially the hours before sunset. In theory, these gaps could be avoided by using geostationary satellites for fire detection. Satellites in the NOAA Geostationary Operational Environmental Satellite (GOES) series have had channels suitable for fire detection since 1983 (Prins and Menzel 1992), and fire detection from these satellites has been incorporated in near-real-time aerosol forecasting (Freitas et al. 2005; Reid et al. 2004) and fire and smoke monitoring (Schroeder et al. 2008b) applications beyond the insular Southeast Asian region. Recently, the Wildfire Automated Biomass Burning Algorithm (WFABBA) developed by the University of Wisconsin Cooperative Institute for Meteorological Satellite Studies (CIMSS) has been applied to the Japan Aerospace Exploration Agency (JAXA) Meteorological Satellite (MTSAT) platform over insular Southeast Asia as part of a global WFABBA geostationary fire monitoring network (Prins et al. 2001). The WFABBA product from MTSAT-1R and MTSAT-2 is the first routine geostationary fire detection product available for this region, providing up to 56 scenes every 24 hours.

Active fire detection from GOES and MODIS has well-documented differences in regard to sensitivity (Schroeder et al. 2008a). The sensors also have differences in regard to radiometric precision, bandpass in fire-measurement channels, thresholds of saturation, and other visual geometric factors (e.g. parallax and atmospheric path length). However, most of the documented differences in fire detection for individual scenes can be attributed to differences in the instantaneous ground field of view (IGFOV) of the pixel. MODIS spatial resolution varies across a swathe from 1 km^2 at nadir to over 9 km^2 at the swathe edge; MTSAT spatial resolution varies from roughly 16 km^2 at nadir to over twice that amount at the western edge of our area of interest. These sensor differences translate into differences in sensitivity to fires, which in turn result in different estimates of fire activity.

In a very recent study, Hyer et al. (2013) analysed the differences in polar-orbiting and geostationary satellites for fire detection in insular Southeast Asia and examined how data from these two systems might be used in a complementary fashion in future studies. They concluded that geostationary fire data have broad-scale spatial and temporal patterns similar to fire observations obtained from polar-orbiting satellites. When aggregated to spatial resolutions of 5° and/or temporal resolutions of 16 days, the spatio-temporal patterns of fire activity from different sensors showed strong correlation. However, correlations between the two different types of datasets were low in full resolution. The lower overall fire detection efficiency of the geostationary sensor analysed (MTSAT) was highlighted. Nevertheless, the results also revealed that the geostationary satellites were able to detect burning occurring typically in late afternoon (Figure 3). Thereby, bias caused by acquisition time from the polar-orbiting satellites could potentially be accounted for and corrected

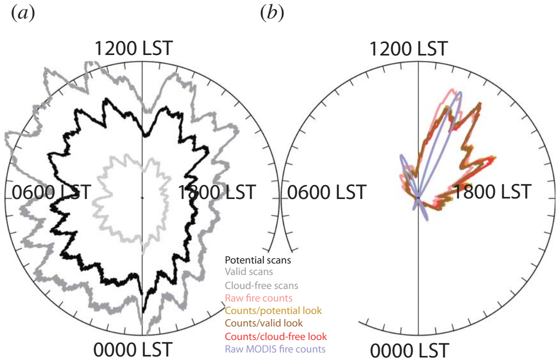

Figure 3. Diurnal cycle of MTSAT coverage (*a*) as well as raw and corrected fire accounts from MTSAT and MODIS (*b*) over the area of interest. Black indicates unfiltered monitoring; dark grey indicates monitoring with usable data; and light grey indicates cloud-free monitoring only. Diurnal cycle of raw MTSAT WFABBA fire counts is indicated in pink. Orange, brown, and red indicate diurnal cycle normalized by potential looks, valid looks, and cloud-free looks, respectively. Uncorrected MODIS fire counts are shown in light blue. Figure taken from Hyer et al. (2013), who also provided a detailed description of the methodology.

using the information from geostationary satellites. Furthermore, the MTSAT WFABBA fire product publicly available for the region showed promise for applications requiring near-real-time estimates of fire activity in Southeast Asia.

The combined use of polar-orbiting and geostationary satellites for active fire detection is a challenging task and requires untangling the competing influences of pixel size, fire diurnal cycle, and location error. Nevertheless, successful creation of such a system would enable estimation of the spatial, temporal, and land-cover patterns of biomass burning in Southeast Asia with an unprecedented level of detail and accuracy.

3.2. Centre for Remote Imaging, Sensing and Processing high-resolution fire monitoring system

One of the major disadvantages of the active fire detection systems discussed above is the low spatial resolution. This is particularly harmful for monitoring smallholder burning due to the small size and short duration of these fires. Medium- to coarse-resolution active fire detection systems are likely to miss a considerable proportion of these fires. High-resolution data, on the other hand, cannot be used to cover large areas on a daily basis. One way to optimize the usability of high-resolution satellites for active fire detection is to use medium- to coarse-resolution datasets to select areas of interest for high-resolution scanning. This type of high-resolution fire monitoring system has been developed in Singapore.

In response to the serious regional haze episode in 1997, the Association of Southeast Asian Nations (ASEAN) Environment Ministers agreed on a Regional Haze Action Plan, which set out cooperative measures needed amongst ASEAN member countries to address the problem of smoke haze in the region arising from vegetation and peat fires. Under this plan, Singapore took up the responsibility of coordinating the regional fire monitoring mechanisms. Since then, the Centre for Remote Imaging, Sensing and Processing (CRISP) at the National University of Singapore (NUS) has undertaken daily fire monitoring using visual interpretation of high-spatial resolution (20–10 m) Satellite Pour l'Observation de la Terre (SPOT) satellite images. Daily hotspot data from coarse-resolution satellite sensors (e.g. MODIS) are used to locate concentrated areas of fire activity within the region. The

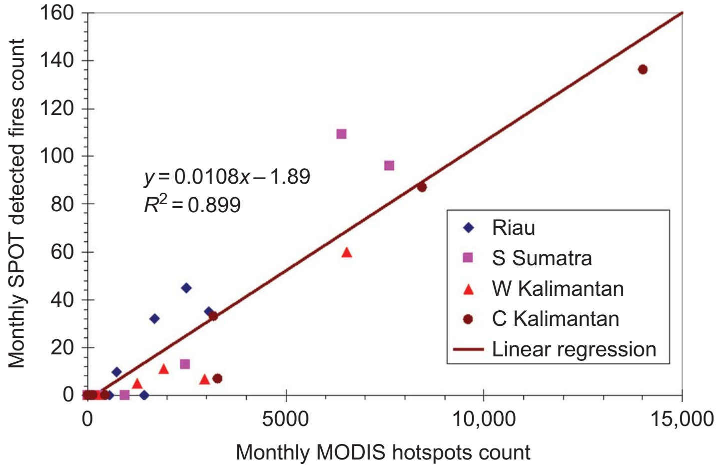

Figure 4. Monthly fire counts in 2006 detected by CRISP monitoring system using SPOT high-resolution data when compared with MODIS hotspot counts in selected high-fire activity provinces in Indonesia. S Sumatra stands for South Sumatra, W Kalimantan for West Kalimantan, and C Kalimantan for Central Kalimantan. Figure taken from Liew, Chia, and Kwoh (2007).

SPOT passes of the following day are then programmed to look at the most active fire areas. The resulting SPOT images are visually analysed using software developed at CRISP to locate individual fires and determine fire type (Lim et al. 1999). Passes of high-spatial resolution SPOT images are inspected every day and reports of fires with annotated images are sent to the National Environment Agency (NEA) of Singapore. The fire report lists for each detected fire: location (longitude and latitude), smoke plume condition (length, width, and thickness), wind direction, and type of land cover (forest, plantation, and agricultural land). The fire reports and annotated images are ready for delivery within 5–6 hours after initial SPOT data have been received.

The synergic use of coarse-resolution (but wide swathe) MODIS hotspot data and high-resolution SPOT imagery has proved successful in acquiring more detailed information on major fires in the region for further analysis. Moreover, analysis has shown that there is a high correlation between SPOT fire counts and MODIS hotspot counts. In 2006, the CRISP active fire monitoring system detected one fire for every 100 hotspots detected by MODIS (Figure 4). This type of high-resolution sampling could in theory be used to derive regional-level estimates on the characteristics of fires at an improved level of detail (e.g. on land-use type, potential origin/purpose of fires, and size of smoke plumes). This, however, is only possible if the high-resolution sample can be shown to include representative proportions of different types of fires taking place in the region.

4. Burnt area mapping in insular Southeast Asian conditions

4.1. Burnt area mapping with medium- to coarse-resolution data

Mapping of burnt areas with medium- to coarse-resolution remote-sensing data is most typically based on the changes in reflectance caused by burning. Fire-induced changes in surface reflectance have been mainly investigated in regions outside insular Southeast Asia, in drier tropical and subtropical climates. Studies based on both ground-based spectro-radiometers (Trigg and Flasse 2000) and MODIS satellite data (Roy et al. 2002; Sá et al. 2003; Li et al. 2004; Loboda, O'Neal, and Csiszar 2007; Veraverbeke, Harris, and Hook

2011) have suggested that spectral separability between burnt and unburnt areas is strongest in the near infrared and shortwave infrared (NIR-SWIR) range of the reflectance spectrum. This has also been brought up by authors working with ATSR (Eva and Lambin 1998b) and SPOT VEGETATION data (Stroppiana et al. 2002; Pereira 2003).

What makes fire-induced reflectance changes in insular Southeast Asia complex is the high variability of pre-fire and post-fire vegetation reflectance caused by the highly varying land-cover characteristics and fire regimes highlighted earlier. In a study on fire-induced changes in insular Southeast Asia, Miettinen (2007) highlighted how the effects of fire changed dramatically between green vegetation-dominated areas and senescent vegetation-dominated land-cover types. The destruction of green vegetation could be detected as a drop in NIR (due to decreased reflection from plant cell walls) accompanied by a simultaneous rise in red wavelength reflectance (due to reduced absorption by chlorophyll) and SWIR (due to reduced absorption by water). Burning of senescent vegetation, on the other hand, merely caused a drop in reflectance values (due to dark ash). These findings agreed well with the results of Silva et al. (2004), who faced similar problems while developing a global burnt area detection algorithm, and are supported by others working outside insular Southeast Asia (e.g. Grégoire, Tansey, and Silva 2003; Pereira 2003) who have highlighted the significance of taking into account the variability of fire-induced spectral changes in burnt area mapping. In the boreal forests, the normalized difference vegetation index (NDVI) has been used to support burnt area detection (e.g. Fraser, Li, and Cihlar 2000) because it accurately detects the destruction of green vegetation, whereas in the dry tropical areas mainly NIR and SWIR bands have been noted to be the best indicators (Roy et al. 2002; Sá et al. 2003). However, in insular Southeast Asia, both of these extremes exist causing marked variation in fire-induced spectral changes even in small geographical regions. Therefore, burnt area detection algorithms should be capable of reliably detecting the burning of both green and senescent vegetation in the insular Southeast Asian region (Miettinen 2007; Miettinen, Langner, and Siegert 2007).

Nonetheless, suitable detection algorithms alone are not enough to enable successful regional burnt area monitoring. The cloudy conditions of humid insular Southeast Asia present another challenge for burnt area monitoring. Apart from a few attempts to apply radar sensors for burnt area mapping (e.g. Liew et al. 1999; Siegert and Hoffman 2000), practically all attempts at automated or semi-automated medium- to coarse-resolution burnt area mapping approaches in this region have been based on multi-temporal analysis of optical remote-sensing datasets. This can be achieved by the creation of multi-temporal composite images or comparing each observation to the previous available observation (or several proceeding observations). Multi-temporal monitoring methods have been tested and used for land-cover and burnt area mapping from regional to global level in both insular Southeast Asia (Fuller and Fulk 2001; Langner, Miettinen, and Siegert 2007; Miettinen and Liew 2008; Hansen et al. 2009) and in other parts of the tropics (e.g. Fernandez, Illera, and Casanova 1997; Barbosa, Pereira, and Grégoire 1998; Stroppiana et al. 2002; Sousa, Pereira, and Silva 2003; Zhang et al. 2003; Silva et al. 2004; Silva, Sá, and Pereira 2005; Hansen et al. 2008; Miettinen, Shi, and Liew 2011b).

In insular Southeast Asia, minimum albedo- and minimum NIR-based compositing methods have shown the most potential for burnt area mapping purposes (Fuller and Fulk 2001; Miettinen and Liew 2008). It is important to remember, however, that these types of minimum value methods must be combined with effective removal of cloud shadows, as has also been pointed out by authors working in other regions (Barbosa, Pereira, and Grégoire 1998; Stroppiana et al. 2002; Sousa, Pereira, and Silva 2003; Chuvieco et al. 2005). Effective cloud removal is particularly important in the humid tropical weather conditions of insular Southeast Asia. The number of available cloud-free observations is generally very low, even though burning typically happens at the driest time of the year. Cloud persistence at this level has serious effects on the usability and reliability of coarse/medium-resolution, large-scale burnt area mapping. This is considered to be one of the main reasons why all global burnt-area mapping systems have faced problems in this region (Roy et al. 2005; Tansey et al. 2008b).

Persistent cloud cover and variable fire-induced changes in reflectance are not, however, the only limiting factors of the usability of medium- to coarse-resolution satellite data for regional burnt area mapping in insular Southeast Asia. Low spatial resolution (250 m–1 km) restricts the detection of small burn scars and therefore reduces the reliability of large-scale burnt area mapping in areas where small burn scars strongly contribute to the total burnt area (Eva and Lambin 1998a). Studies performed in Africa and Australia have suggested clear connections between land-cover type and the performance of coarse-resolution burnt area mapping (e.g. grassland vs forest) (Eva and Lambin 1998a; Stroppiana, Grégoire, and Pereira 2003; Silva, Sá, and Pereira 2005). These have explained the differences mainly by reference to smaller burn scar size in forest ecosystems, which was also mentioned by Bucini and Lambin (2002). However, these results do not seem to be directly applicable to insular Southeast, where all land-cover types have been shown to include both small and large scars in varying proportions, depending on the location of the study site (Miettinen, Langner, and Siegert 2007; Miettinen and Liew 2009).

The weak correlation between burn scar size and land-cover type in insular Southeast Asia can be explained by the fact that burning does not happen in natural ecosystems in this region. Practically all biomass burning in insular Southeast Asia is caused by human activities and it takes place mainly in managed or degraded ecosystems (Bowen et al. 2001; Miettinen, Langner, and Siegert 2007). Instead, burn scar size has been found to be strongly correlated with the occurrence of peat soil. Miettinen and Liew (2009) revealed that in wetlands, 89% of the burnt area was found in burn scars larger than 0.25 km^2, whereas outside wetlands, only 35% of the overall burnt area was represented by burn scars larger than 0.25 km^2. Figure 5 further illustrates the striking difference in size distribution of burn scars between wetlands and other areas.

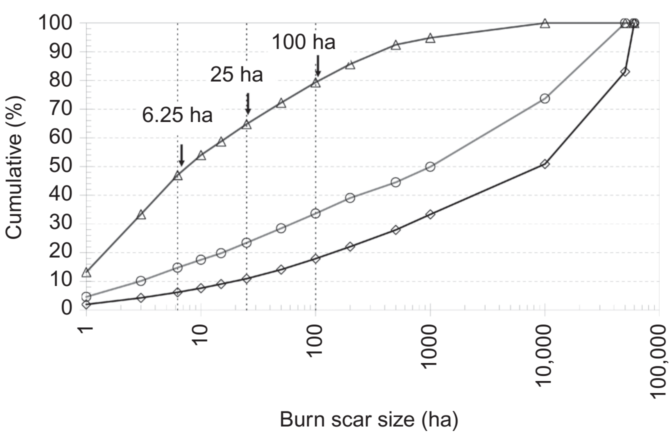

Figure 5. Cumulative percentage of burnt area by burn scar size (ha). Diamonds refer to peat soil, circles to alluvial soil, and triangles to non-wetland areas. The *x*-axis scale is set to logarithmic in order to create a more visually meaningful figure, given the wide range of burn scar sizes. Burn scar sizes corresponding to typical spatial resolutions of medium/coarse-resolution satellite sensors (250 m resolution → to 6.25 ha area, 500 m → to 25 ha, and 1 km → to 100 ha) have been highlighted. Figure taken from Miettinen and Liew (2009).

Interaction between climate variation and fire size distribution leads to considerable interannual variation in the efficacy of medium- to coarse-resolution satellites for burnt area estimation in insular Southeast Asia, mainly determined by the severity of the fire season in the peatland areas (Miettinen, Shi, and Liew 2011a). Similar issues related to spatial resolution have been shown to markedly affect intra-annual burnt area mapping efficacy within a burning season in the African savannas (Laris 2005). It is possible to calibrate medium- to coarse-resolution burnt area mapping results with high-resolution sampling to estimate the total burnt area (Eva and Lambin 1998a; Silva, Sá, and Pereira 2005). However, this approach produces reliable results only if the distribution of different fire regimes occurring in the area can be determined and representative high-resolution samples from each fire regime can be obtained. Furthermore, the calibration approach cannot provide spatial distribution of the burnt areas.

4.2. Burnt area mapping with high-resolution data

Because of the prevalence of fires <0.25 km^2, high-resolution satellite datasets (<30 m) would be needed to map burnt areas reliably throughout insular Southeast Asia. However, automatic burnt area mapping using high-resolution satellite data is seriously hampered by the availability of images, nearly all of which are to some extent affected by cloud, cloud shadow, and other atmospheric effects. In addition to cloud issues, haze may be a serious problem for burnt area detection, especially during major fire events. To date, we are not aware of any automated burnt area detection system using high-resolution satellite data having been developed for this region. However, Broich et al. (2011) have recently shown the usability of historical time series analysis of high-resolution Landsat data for deforestation mapping in insular Southeast Asian conditions. In theory, a somewhat similar change-detection approach could be used for burnt area mapping, although in reality the scarcity of cloud-free observations combined with the more dynamic nature of burn scars (vs land cover) would most likely render the results meaningless in most cases. Unless the temporal frequency of available high-resolution data dramatically increases in the future, any automated high-resolution burnt area mapping approach in this region would most likely have to be based on the detection of burnt areas on single images rather than change detection in a series of subsequent observations.

Case-by-case assessments of burnt areas at both local and regional levels have been made using high-resolution satellite data in insular Southeast Asia (Liew et al. 1998; Page et al. 2002; Miettinen and Liew 2005, 2009). These assessments were based on either purely visual or semi-automatic burnt area mapping approaches. Burn scars can be detected on high-resolution satellite images by visual interpretation, but the work is laborious and time-consuming (see, for example, Figure 2). The process can be somewhat accelerated using automatic image clustering/segmentation procedures to reduce the amount of manual work needed.

The most extensive visual burnt area mapping initiative in insular Southeast Asia to date has been the effort to map the burn scars of the 1997–1998 fire episode using SPOT satellite Quicklook images ($\sim$100 m resolution) conducted at CRISP in Singapore (Liew et al. 1998). The estimated burnt area for 1997 derived from this mapping was 20,800 km^2 in Sumatra and 35,800 km^2 in Kalimantan. The 1998 burnt area was estimated at 25,100 km^2 in East Kalimantan, 5300 km^2 in Sabah, and 900 km^2 in Sarawak and Brunei. However, this type of mapping would have been impossible to conduct using fully automated change-detection methods due to the limited number of usable high-resolution images in the extreme conditions prevailing during the final stages of a major fire event.

Automated mapping of burn scars with high-resolution satellite data is a problem particularly with large fire events because they are extinguished by the onset of the rainy season, which prevents the capture of good post-fire images, while images captured during the fire event are likely to be obscured by haze of varying intensity.

As an example of a new type of data source that may enable improved high-resolution burnt area mapping in the insular Southeast Asian conditions, one could mention the 6.5 m spatial resolution RapidEye constellation (http://www.rapideye.net/about/constellation.htm) and the 10–20 m spatial resolution Sentinel-2 constellation (http://www.esa.int/esaLP/SEMM4T4KXMF_LPgmes_0.htlm). These types of satellite constellations with a frequent revisiting interval (1–5 days) could potentially be used to collect adequate post-fire imagery within the first 1–2 months after serious fire events, even in the difficult atmospheric conditions of this region. Naturally, the problems with automated burnt area detection with high-resolution data would remain and thus image interpretation would most likely have to resort to semi-automated methods. Nevertheless, these new types of constellation may offer technical capabilities in the future to quantify the extent and distribution of burnt areas at an unprecedented level of detail after extraordinary fire episodes.

4.3. Burnt area estimation with active fire data

Active fire detection can be used in burnt area mapping either in a supportive role or as the main source of information. In boreal regions, active fire datasets have been used mainly to identify fire areas, with further analysis of reflectance to map burn scars (Fraser, Li, and Cihlar 2000; Lee et al. 2002; Sukhinin et al. 2004). Hotspots have been typically used as seeds or indicators of burn scars in various approaches taking advantage of region growing algorithms. Active fire detection can also be used to locate training samples to define spectral characteristics for burnt areas (Roy et al. 2005). Note, however, that this type of spectral signature extraction is likely to face serious problems in the humid tropics due to the high proportion of small burn scars, which leads to mixed pixel effects. Active fire data have also been used as the basis of a global burnt area estimation method correlating active fire detection with burnt-area mapping results (Giglio et al. 2006b). It must be noted, however, that Giglio et al. (2006b) pointed out that this approach faced serious problems, particularly in persistently cloudy humid tropics like insular Southeast Asia.

In local- and regional-level studies taking place in insular Southeast Asia, hotspots have been used both as supporting information for burnt-area mapping (Siegert and Hoffmann 2000) and as the main source of data to estimate burnt areas (Langner, Miettinen, and Siegert 2007; Langner and Siegert 2009). However, there are several serious problems in regard to hotspot-based burnt area estimation. First, active fire detection does not provide an exact location. The hotspot coordinates merely represent the centre location of the (typically 1 km^2) cell that had shown temperature anomalies. The fire may have taken place anywhere within the instantaneous field of view of the sensor. Second, active fire detection does not reveal the size of the burn scar. The burnt area in the detected location may not be 1 km^2 in size (or whatever the image pixel size is) but can vary significantly depending on the characteristics of the fire event (Calle, Casanova, and Romo 2006). And third, the same fires may be detected several times by successive satellite passes, causing overlap in the burnt areas. There are many ways to utilize active fire detection for burnt area estimation but, regardless of the methodology used, the estimates should be calibrated using high-resolution datasets.

Calibration efforts in insular Southeast Asia have shown that active fire-based burnt area estimation can produce more consistent results for total burnt area over the wide range of land cover and soil types than medium- to coarse-resolution burnt area mapping (Miettinen, Langner, and Siegert 2007). However, other studies have also revealed significant variation in the ratio between active fire-based burnt area estimates and high-resolution reference datasets within the region depending on the dataset used, fire regime, land cover, and soil type, as well as on the way in which burnt area estimates are derived from active fire data (Stolle et al. 2004; Miettinen, Langner, and Siegert 2007; Tansey et al. 2008a). It is essential to have information on fire regime distribution (and thereby land cover, land use, and soil type distribution) in the region for a reliable estimation of burnt area based on hotspot detection in insular Southeast Asia. Because the fire regime is variable from year to year, significant yearly variation in calibration factors is likely to occur (Miettinen, Shi, and Liew 2011a; Reid et al. 2013).

Calibration efforts performed in this region have suggested overall underestimation of burnt area from active fire datasets (Figure 6), and this is supported by studies performed in other parts of the world (e.g. Eva and Lambin 1998a; Li et al. 2000). Active fire-based methods underestimate the extent of the burnt area mainly due to the missing of fires, and this results from their small size or short duration and cloudiness. These methods can be calibrated to compensate for missed fires, but at the expense of accuracy in the spatial fire pattern. Furthermore, strong calibration may cause overestimation of burnt area in some parts of the region of interest due to local variation in the fire-detection efficiency. Randriambelo et al. (1998) showed that overestimation of the burnt area is possible, particularly if the proportion of sub-pixel-sized burn scars in a given area is large. In the dominant land cover/land use types in insular Southeast Asia (e.g. smallholder-dominated areas), evidence suggests that missing fires are the largest effect, and active fire-based methods generally underestimate the area burnt (Stolle et al. 2004; Miettinen, Langner, and Siegert 2007). This is mainly due to persistent cloud cover, low-intensity ground fires, or

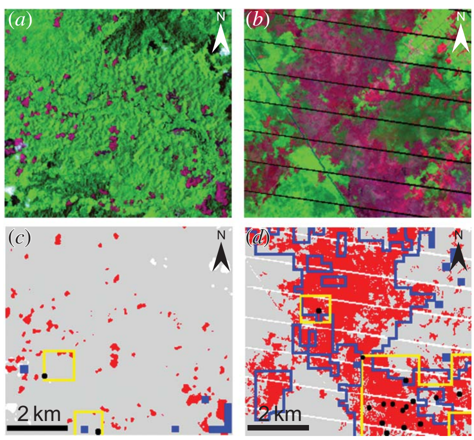

Figure 6. Examples of differences in active fire and reflectance-based burnt-area monitoring in two different types of fire. Smallholder burning in mineral soil (*a*) and large-scale wildfires in peatland (*b*) seen on Landsat ETM+ images (*a*) and (*b*), as well as burnt area detection results (*c*) and (*d*). Red indicates reference burnt area, blue the borders of MODIS reflectance-based detection in 250 m resolution and yellow the borders of MODIS active fire-based detection in 1 km resolution, while black dots represent hotspots. Note that in this case the conversion from active fires to burn scars was made so that a cell in a standard 1 km grid over the study area was considered burnt if one or more hotspot locations were found within the cell. Figure taken from Miettinen, Langner, and Siegert (2007). (Landsat RGB: 743).

quickly spreading fires in alang-alang (*Imperata cylindrica*) grasslands, all of which lower the efficiency of active fire detection in this region.

The efficiency of active fire detection, and thus the effect of calibration to account for missed fires, may vary markedly with land-cover type in insular Southeast Asia. Miettinen, Langner, and Siegert (2007) and Tansey et al. (2008a) have noticed high numbers of active fires associated with small burnt areas in forests and also in peatland areas to some extent in other land-cover types. They explained this by the relatively long-lasting forest and peat fires compared with those in managed and more open vegetation types in mineral soils, which spread quickly and burn for only short periods of time. Short-lived fires may not be detected by satellites that pass over the area only a couple of times per day, whereas long-lasting fires are detected several times. Densely vegetated areas also generally have cooler and more homogeneous backgrounds, thus leading to improved efficiency in thermal contrast detection methods (Schroeder et al. 2008a). Hotspot-based burnt area estimation is thus likely to have a significant bias towards forested areas and peatlands in this region, especially if the conversion from active fire detection to burnt area is based merely on number of hotspots, not taking into account the location of the fire. Peatland fires usually progress slowly, and the same fires may be detected several times in nearly the same locations. This effect of overlapping fires can be circumvented by rasterization of hotspot data into a 1 km grid (each grid cell with one or more hotspots is considered burnt regardless of the number of hotspots within the cell), allowing more reasonable burnt area estimates in peatlands and slowly progressing forest fires (Figure 6, Langner, Miettinen, and Siegert 2007; Miettinen, Langner, and Siegert 2007; Langner and Siegert 2009). In any case, it has to be remembered that active fire-based burnt area mapping cannot in any circumstances be used to delineate burn scars in areas of heterogeneous land cover, since the exact location and borders of the scars are not known (Hyer and Reid 2009). Even at its best, it can only be used to produce calibrated general estimates of the extent and approximate distribution of burnt areas within the region.

5. Conclusion

In this review article, we have analysed the current status of knowledge on fire monitoring in insular Southeast Asia. We have highlighted how the special characteristics of the region affect all types of remote-sensing-based regional-level fire monitoring, and we conclude that the currently used monitoring methods have serious limitations in this region that directly affect the reliability of fire and burnt area monitoring results.

The most fundamental issue affecting fire activity monitoring in insular Southeast Asia is the size distribution of burn scars. Soil type has been shown to be a good indicator of burn scar sizes in this region (at least under the prevailing land-management practices), and medium-resolution burnt area mapping has been found to be potentially usable for burnt area monitoring in peatland areas (Miettinen, Langner, and Siegert 2007; Miettinen and Liew 2009). Although this is important due to the significance of peatland areas in haze production and carbon emissions (Qadri 2001; Page et al. 2002; van der Werf et al. 2008), concentrating on peatlands ignores all fire activity taking place on mineral soils, which in wetter years represents the majority of fire activity in this region (Miettinen, Shi, and Liew 2011a). With the methods currently available, regional-level fire activity monitoring in mineral soils is limited to active fire detection, greatly handicapped by the typically small size and short duration of land-preparation fires as well as by the frequent cloud cover in this region.

In summary, we believe that future monitoring methods of fire activity in this humid, tropical, and densely populated region of insular Southeast Asia will need a spatial and temporal resolution sufficiently high to enable detection of all three major types of fire activity taking place in this region (smallholder land-preparation fires, large-scale land-conversion/preparation fires, and wildfires). Most notably, the inclusion of smallholder fires in monitoring schemes is crucial to providing reliable data for the sophisticated and detailed models used to evaluate the effects of fire activity in the economy, ecology, and air quality of this region. Reaching these objectives may require utilization of combinations of high- and medium-spatial resolution sensors with lower-resolution polar-orbiting and geostationary satellites. With the materials and methods currently available, the level of burnt area in this region is consistently underestimated in global burnt area estimations. Subsequently, this causes underestimation of the global effects of insular Southeast Asian fire activity.

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