Vegetation Fires in the Asian Region: Satellite Observational Needs and Priorities

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Abstract

Fire plays important role in shaping ecosystem structure and function. Depending upon the complex effects of fire, it can have either beneficial or harmful effects. Remote sensing technology with its synoptic, multi-temporal, multispectral and repetitive coverage capabilities can provide valuable information on fire counts, radiative power, area burned and vegetation type. In this article, we briefly review the potential of satellite remote sensing data for mapping and monitoring vegetation fires. For describing fire events in Asia, we used nine years of MODIS datasets in conjunction with the MERIS 300m vegetation map. In several regions of the world, including Asia, scientists are looking forward to an improved understanding of the utility of satellite products for resource management and policy. To meet such requirements, an international program called Global Observation of Forest Cover/Global Observations of Land Dynamics (GOFC-GOLD) has been coordinating forest, land and fire activities across the globe. More specifically, the GOFC-GOLD Fire Implementation Team (IT) has been involved in articulating the use of satellite-derived fire products and information from existing and planned systems for global change research, fire management and policy decision-making. Accordingly, a brief description of GOFC-Fire IT's activities, goals and strategies is provided. Satellite observational needs and priorities for effective fire monitoring in the Asian region are also discussed.

Key words: Asia, GOFC-GOLD, MODIS data, vegetation fires

1. Introduction

Vegetation fires across the world, including the Asian region, have received increasing attention because of a wide range of ecological, economic, social and political impacts. The role of fire in the creation and maintenance of landscape structure, composition, function and ecological integrity has been well recognized (Goldammer, 1990; Pyne *et al*., 1996; Roberts, 2000; Saha, 2002; Dennis *et al*., 2005). At the local scale, fire can stimulate soil microbial processes and combust vegetation, ultimately altering the structure and composition of both soils and vegetation (Agee, 1994; De Bano *et al*., 1998). Also, at the regional and global scales, combustion of forest and grassland vegetation releases large volumes of radiatively active gases, pyrogenic aerosols, and other chemically active species that significantly influence the Earth's radiative budget and atmospheric chemistry (Andreae & Merlet, 2001), impacting air quality (Hardy *et al*., 2001) and risks to human health (Brauer, 1999; Sastry, 2000).

Historically, in the Asian region, fires were thought to be confined to open deciduous forest and savanna forest ecosystems (Johnson & Dearden, 2009). However, satellite remote sensing data as detected from the MODIS sensor reveal that fires occur over a variety of geographical regions (Fig. 1) covering diverse ecosystems including tropical evergreen forests, closed deciduous forests, mixed forests, scrub lands, agricultural areas, etc. (Fig. 2a-c; Fig. 3). Fires in the Asian region are associated with environmental and economic losses, including health hazards. For example, recent estimates suggest that the peat lands of Southeast Asia cover approximately 250,000 km^2 (Carbopeat, 2011) and represent an immense reservoir of fossil carbon (Page *et al*., 2002; Jaenicke *et al*., 2008). CO_2 emissions from peat fires are estimated at about 30% of global CO_2 emissions (Hooijer *et al*., 2006). Previously, in Indonesia, the area burned in the catastrophic fires of 1997/98 was estimated at 9.7 million hectares of forest and non-forest land, with some 75 million people affected by smoke, haze and the fires themselves. Impacts included damage to health, loss of life and property and reduced livelihood options. The economic costs were estimated to exceed 9 billion USD (Barber & Schweithelm, 2000). The impacts of the resulting atmospheric pollution on health, transport and

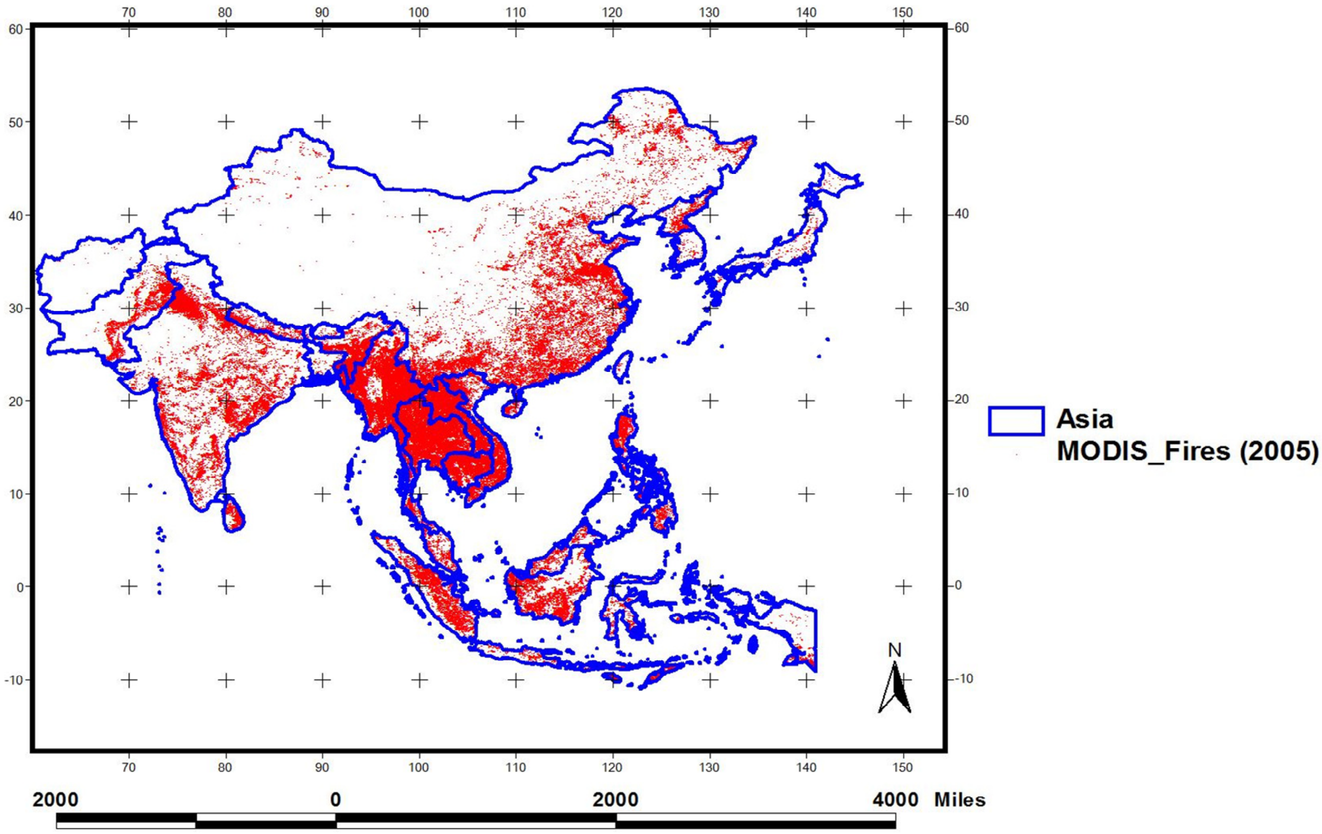

Fig. 1 MODIS-derived active fires in the Asian region (2005).

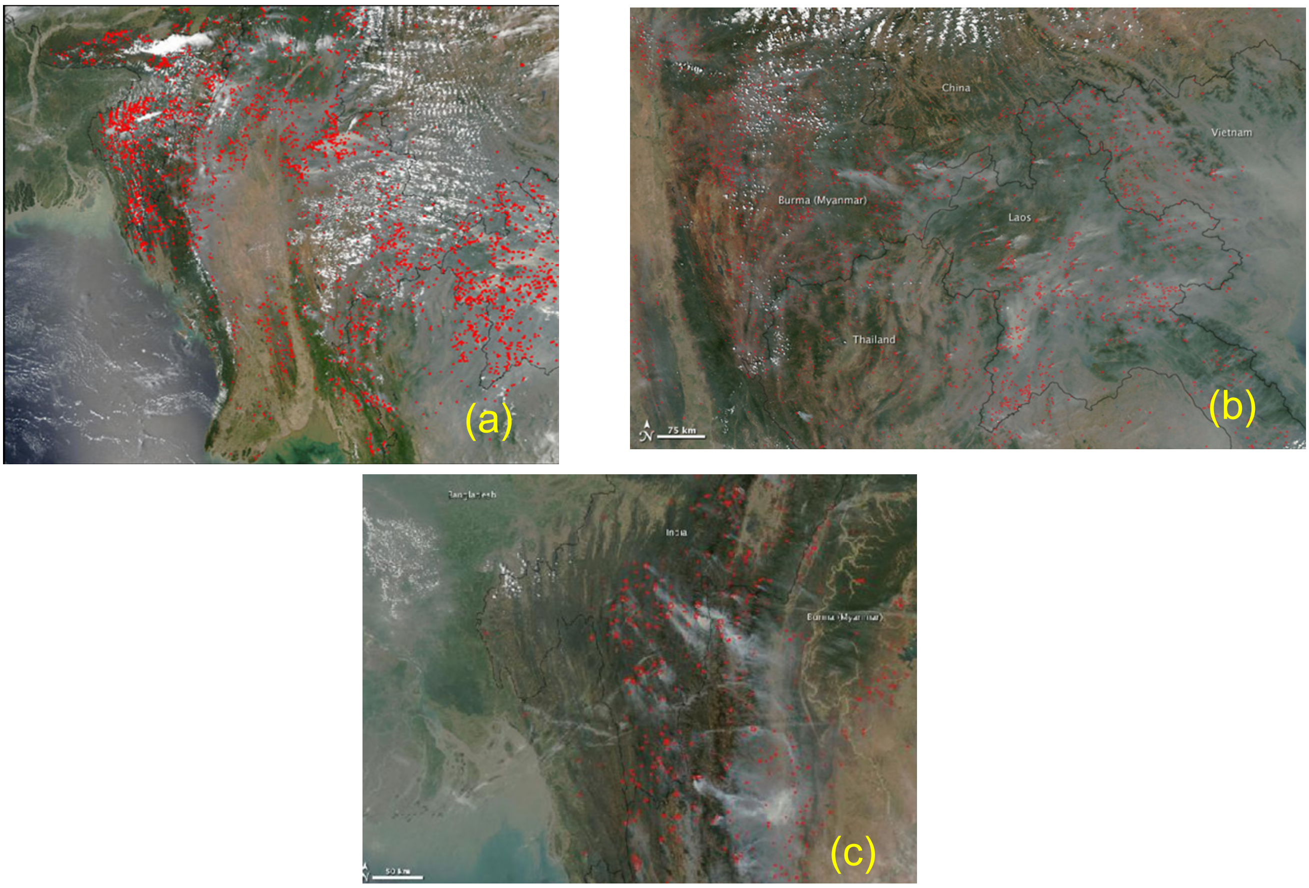

Fig. 2 MODIS-derived vegetation fires: a) April 8th, 2003, Burma; b) March 05, 2010 South-East Asia; c) March 4th, 2010, India and Myanmar.

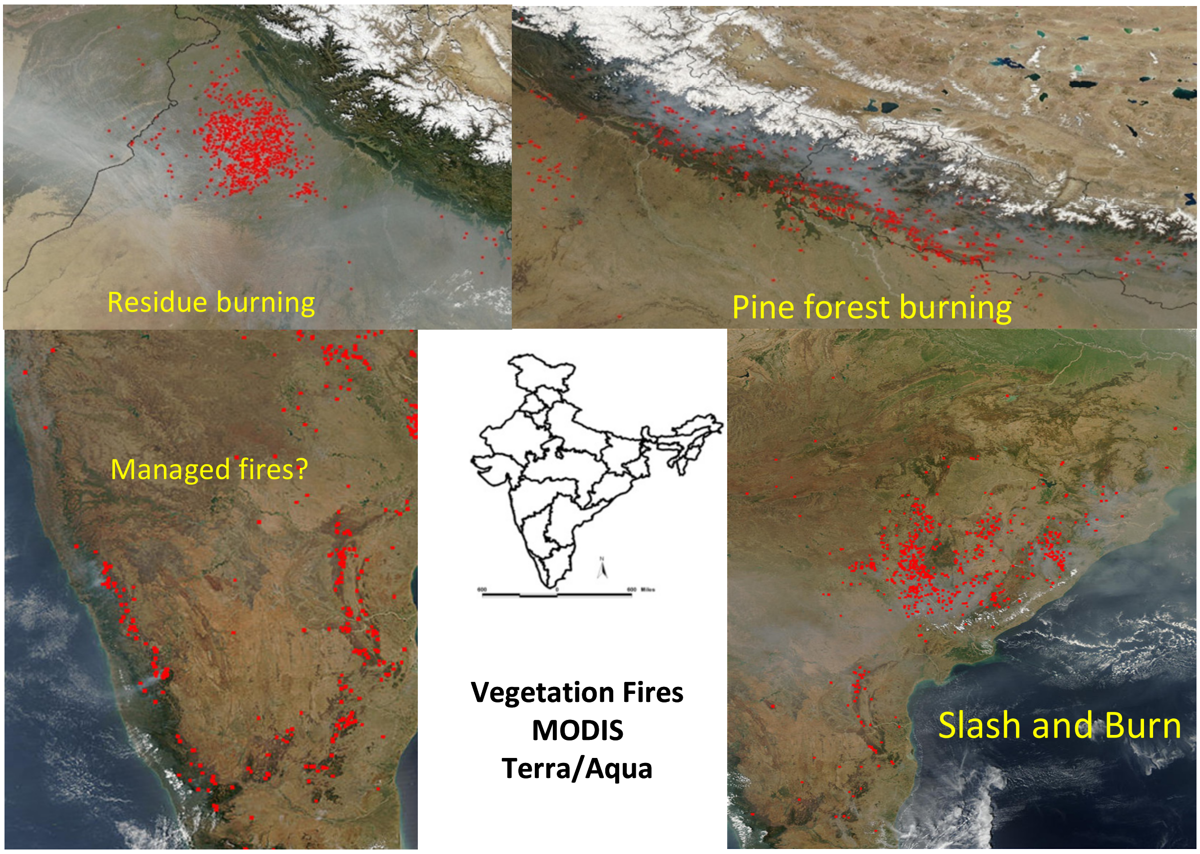

Fig. 3 MODIS-derived vegetation fires in the Indian region.

tourism were borne largely by Indonesia, Brunei Darussalam, Singapore and Malaysia (Radojevic, 2003). Similarly, in India, the Himalayan forest fires during 1995 consumed nearly 6 Mha and caused huge economic losses (Bahuguna & Upadhyay, 2002). The regular agricultural residue burning events that occur to-date in the Punjab region of India were shown to cause enormous pollution problems, enhancing direct radiative forcing in the Indo-Ganges region (Ramanathan & Carmichael, 2008; Vadrevu *et al*., 2011). Chan *et al*., (2000) from Ozonesonde profiles, satellite fire counts, CO data and back-air-trajectory analysis, showed that biomass burning emissions in Southeast Asia are a source of ozone enhancement in the lower troposphere in springtime over Hong Kong. More examples of the impacts of fires in the Asian region and on the local environment can be found in Smith *et al*. (1996); Christopher *et al*. (1998); Streets *et al*. (2003); Akimoto (2003); Venkataraman *et al*. (2006); Lau & Kim (2006); Badarinath *et al*. (2007); Ramanathan & Carmichael (2008); Vadrevu *et al*. (2011), etc. The causative factors of fires in the Asian region have been mainly attributed to slash and burn agricultural practices, agricultural residue burning to prepare for the next crop rotation, unsustainable forestry and plantation development including for timber products, plywood, palm oil, etc., clearing of peat lands to establish rice production in Kalimantan, management of feed for grazing animals in national parks, etc. (Schmidt-Vogt, 1998; Fox *et al*., 2000; Siegert *et al*., 2001; Stolle *et al*., 2003; Gupta *et al*., 2004; Murdiyarso *et al*., 2004; Butchiah *et al*., 2009). In addition, the role of climate factors cannot be overlooked. For instance, regional haze events in Indonesia during 1982, 1983, 1987, 1991, 1994, 1997, 1998 and 2002 were reported to be tightly coupled with El Niño events (de Groot *et al*., 2006).

Accurate information on fires (location, frequency, extent, seasonality, etc.) is necessary for making strategic and informed decisions on fire management by local authorities and civil protection agencies. A combination of space- and ground-based observations are necessary for monitoring fires. The transboundary dimensions of fire impacts and air pollution necessitate organized efforts to understand, plan and implement effective responses. While some countries within the Asian region have developed their own organizational setup through which fire management strategies are carried out (*e.g.*, India, Japan, Singapore, Indonesia, etc.) several others lack such systems.

In this study, we briefly review the potential of satellite remote sensing data products for use in fire mapping and monitoring, followed by a detailed analysis of the latest fire situation in the Asian region. For describing regional fire events spatially and temporally, we use the MODIS active fire product (Justice *et al*., 2011). We also use 300m MERIS vegetation product to assess vegetation-fire statistics over the entire region. Since successful fire management depends on fire prevention, detection and preemptive suppression measures, we call for an increased role for regional scientists in developing, calibrating and validating fire products at a local scale through active involvement with other international scientific communities such as the Global Observation of Forest Cover-Global Observation of Land Cover Dynamics (GOFC-GOLD) – Fire Implementation Team (IT). Accordingly, an overview of GOFC-Fire IT's activities has been highlighted along with its goals and strategies. Satellite as well as ground-based observational needs for effective fire monitoring in the Asian region are also highlighted.

2. Satellite Remote Sensing of Fires

Over the past few decades, spatial information technologies have been widely used in vegetation fire studies (Justice *et al*., 2002; Giglio *et al*., 2003; Roy *et al*., 2005). Remote sensing with its multi-temporal, multi-spectral, synoptic and repetitive coverage can provide valuable information on fire counts, area burned and types of ecosystems burned (Justice *et al*., 2003). Csiszar *et al*., (2009) highlighted a variety of satellite products useful for Fire research in the context of the Global Terrestrial Observing System's (GTOS) Essential Climate Variables. Broadly, satellite derived fire datasets can be categorized into three different types:

A) Active fire products: fires emit thermal radiation with a peak in the middle infrared region, in accordance with Planck's theory of blackbody radiation. Therefore, active fire sensing is often undertaken using middle infrared and also thermal infrared (usually around 3.7 to 11 mm) satellite bands (Dozier, 1981). Active fire count data from ATSR, MODIS, etc., can be used to characterize seasonal and geographic variations in fire occurrences. Higher resolution systems such as ASTER and Landsat 7 have been used to identify active fires, albeit with less frequent coverage (Giglio *et al.*, 2008).

B) Burned areas: satellite measurements in the near- and short-wave infrared are sensitive to changes in surface reflectance caused by burning. Mapping of burned areas mostly relies on detecting changes in vegetation indices although other more sophisticated approaches are available (Roy *et al*., 2005; Giglio *et al*., 2009). Currently, the burned areas can be retrieved from LANDSAT, SPOT, AWiFS, MODIS, etc. Some of the burnt area products derived from satellites include Global Burned Areas (L3JRC), GBA 2000, GLOBSCAR, MODIS burned area product, GLOBCARBON, etc.

C) Fire radiative energy products: instantaneous fire radiative power (FRE) measured from middle infrared satellite bands can be used to estimate the amount of biomass burned (Wooster *et al*., 2003). Recently, Vermote *et al*. (2009) and Boschetti and Roy (2009) demonstrated methodologies for calculating FRE, useful in emissions estimation. Some of the active fire products with FRP information include GFED, WFABBA, MODIS FRP, SEVIRI FRP, etc.

Some of the satellites useful for fire products generation are listed and described in Fig.4. MODIS-based fire products can be accessed through the University of Maryland webserver, http://modis-fire.umd.edu/Burned_Area_Products.html.

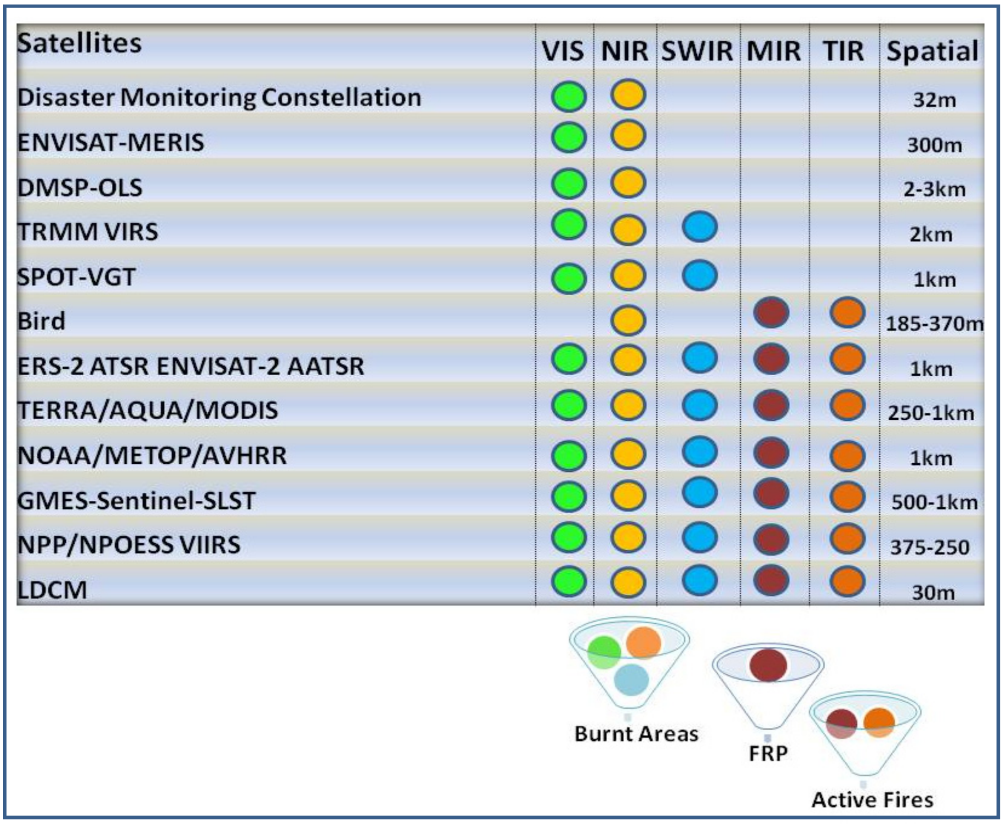

Fig. 4 Satellites useful for fire product generation.

3. Vegetation Fires in the Asian Region

In this study, we used the MODIS active fire datasets from 2002-2010 for analysis of fire events in the Asian region. The MODIS active fire product detects fires in 1 km pixels that are burning at the time of overpass under relatively cloud-free conditions using a contextual algorithm. It first applies thresholds to the observed middle-infrared and thermal infrared brightness temperature and then rejects false detections by examining the brightness temperature relative to neighboring pixels (Giglio, L. *et al*., 2003). Fire frequency refers to the number of fires over a given period. The aggregated yearly MODIS fire counts for 2002-2010 for different countries are shown in Fig. 5 and average fire counts in Table 1. An average of 382,455 fire counts per year was recorded from the Asian region. Of the different countries, Myanmar recorded the highest number of fires followed by India, Indonesia, China, Laos, Thailand, Cambodia, Vietnam, and others. These seven countries accounted for 92.4% of all fires in the Asian region. Macao and the Maldives recorded no fire events during the nine-year period. Spatial distributions of fire events for the typical fire year of 2005 are shown in Fig. 1 and monthly variations in Fig. 6. The results suggest that seventy-five percent of all fires occur between January and May in the Asian region, with the peak fire season in March. Further, MODIS Aqua captured 70% of the fires relative to MODIS Terra (Fig. 7), suggesting that most of the biomass is burned during the late afternoon.

For analyzing the fire occurrences in individual vegetation categories, we used the MERIS 300 m vegetation product which was created using an automatic and regionally-tuned classification of time-series of 300 m MERIS full-resolution mosaics from December 2004 to June 2006 (Bicheron *et al*., 2008). The map consists of 22 land cover classes using the Land Cover Classification System (LCCS) and a more detailed Level-2 legend. Figure 8 shows a map of the Asian region. MODIS fire count data for the year 2005 were overlain on the MERIS vegetation map and analyzed for spatial variations. Of the different vegetation types, fire counts in the closed to open shrub land category dominated at 18.8%, followed by closed to open, broadleaved evergreen-semi deciduous forest, rain fed croplands (16.9%), post-flooded or irrigated croplands (12.0%), mosaic cropland vegetation (10.55%), mosaic vegetation/cropland (9.98%), etc. (Fig.9). These results clearly suggest that in addition to forest fires, agricultural fires in the Asian region are also important to consider for addressing fire management and mitigation options.

To locate geographical regions of high fire incidences, a hotspot analysis was carried out using the K-means clustering algorithm. The K-means clustering algorithm partitions ‘n’ observations into ‘k’ clusters, in which each observation belongs to the cluster with the nearest mean. It is similar to the expectation-maximization algorithm for mixtures of Gaussians (MacQueen, 1967; Kanungo *et al*., 2002). The spatial clusters delineated using the K-means algorithm are shown in Fig. 10.

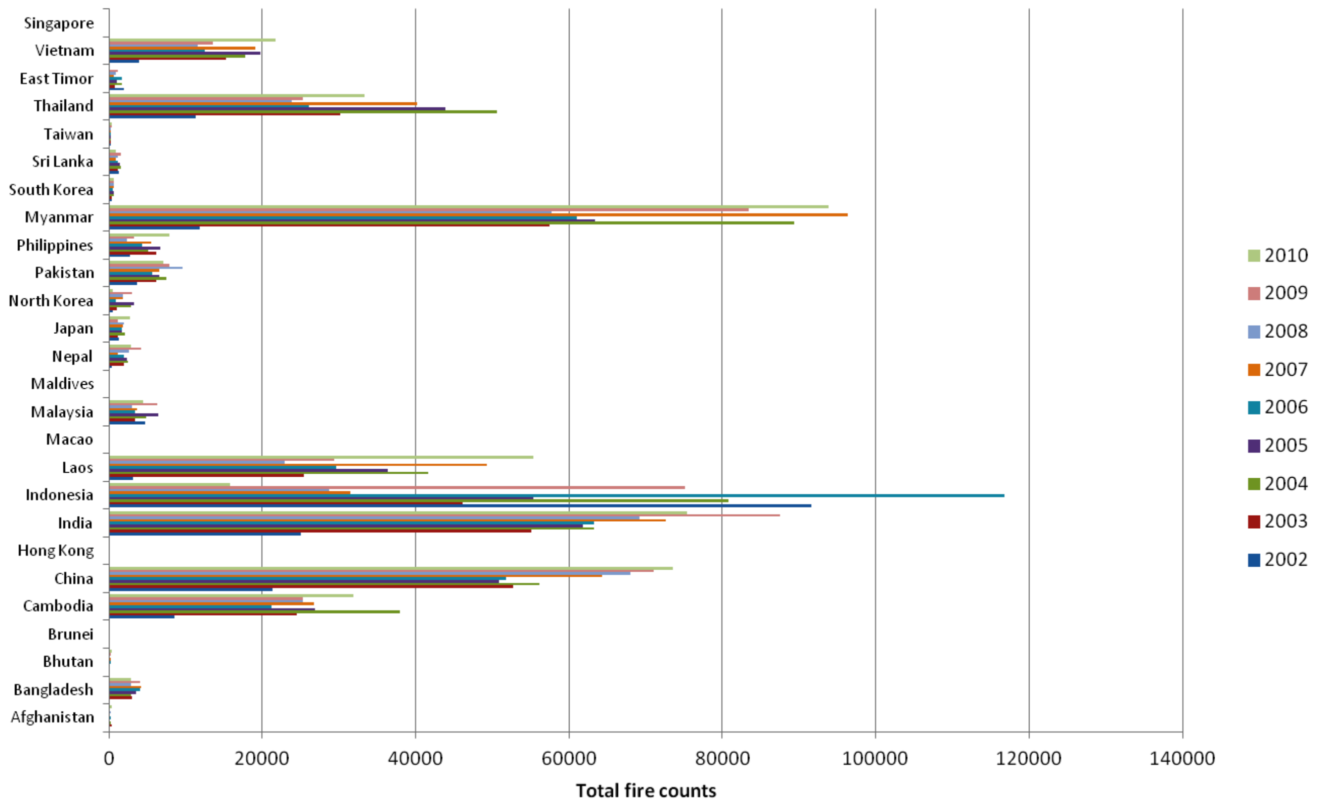

Fig. 5 Vegetation fire statistics in the Asian countries derived from MODIS datasets

Table 1 Annual average fire occurrences (active fires) in different countries derived from nine years of MODIS Active Fire data (2002-2010).

Country	Annual Fire counts	% contribution
Afghanistan	248	0.065
Bangladesh	3113	0.814
Bhutan	209	0.055
Brunei	35	0.009
Cambodia	25360	6.631
China	56668	14.817
East Timor	1128	0.295
Hong Kong	69	0.018
India	63696	16.654
Indonesia	60224	15.747
Japan	1771	0.463
Laos	32601	8.524
Macao	0	0.000
Malaysia	4515	1.181
Maldives	0	0.000
Myanmar	68279	17.853
Nepal	2230	0.583
North Korea	1772	0.463
Pakistan	6748	1.764
Philippines	4926	1.288
Singapore	7	0.002
South Korea	578	0.151
Sri Lanka	1277	0.334
Taiwan	307	0.080
Thailand	31643	8.274
Vietnam	15051	3.935
Total	**382455**	**100**

The cluster analysis reveals that the fire hotspots are located in the northwestern regions of India, comprising the Indo-Gangetic plains, a hotspot of agricultural residue burning events. Fire clusters in central India covering Uttar Pradesh and Chattisgarh, including southern Andhrapradesh were associated with tropical deciduous forest burning, whereas fire clusters in parts of Tamilnadu, Karnataka (southern India), Assam and Mizoram (northeastern India) were attributed to evergreen forest burning. A relatively large cluster of fires was noted in the northeastern Yunnan region of China spreading towards the south with extensive but relatively small fire clusters in Myanmar, Laos, Cambodia, and Vietnam, continuing to Surat-Tani Province in Thailand, covering a variety of ecosystems (Fig. 10). Clusters of fires were also observed in Riau, Sumatra, Kalimantan (Indonesia) and East-Timur, some of which were associated with peatland burning. Fires in Abra, Apayo of the Philippines were linked to slash and burn, including pine forest burning in the mountain provinces. Fires extending from Hainan Province in the lower northeast of China up to Jilin Province in the upper northeast can also be seen in Fig. 10, along with other fires mainly attributed to

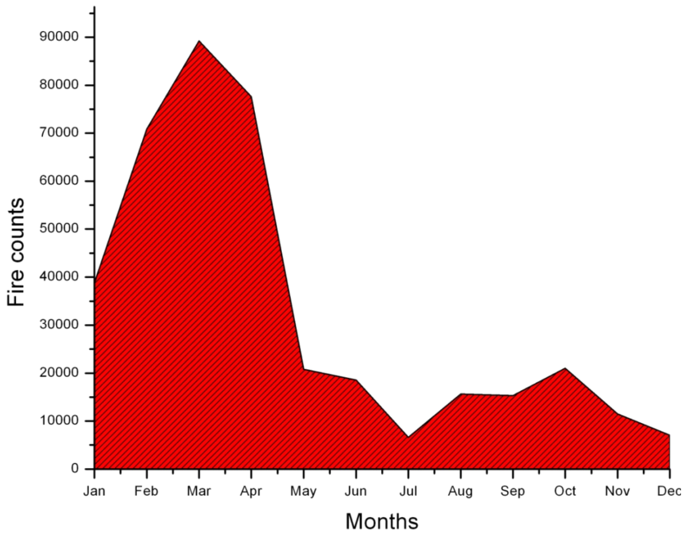

Fig. 6 Monthly variation in fire occurrences in the Asian region.

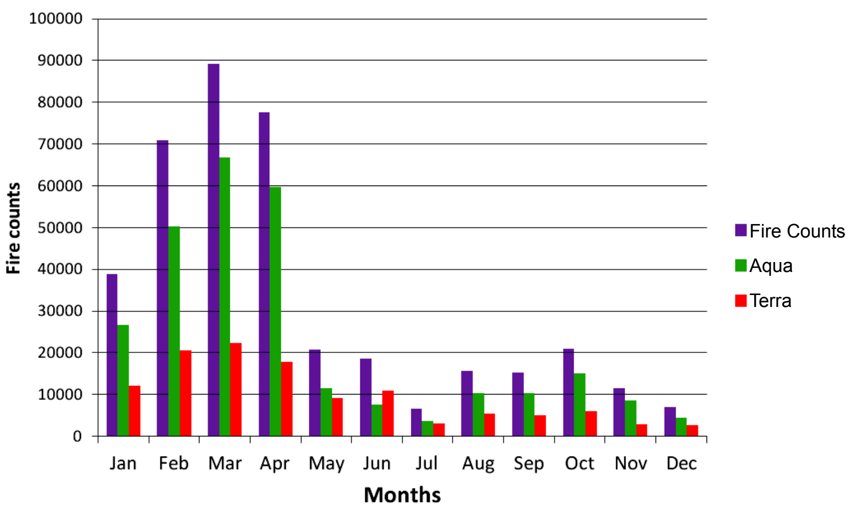

Fig. 7 Monthly variation in Aqua and Terra MODIS fire occurrences in the Asian region.

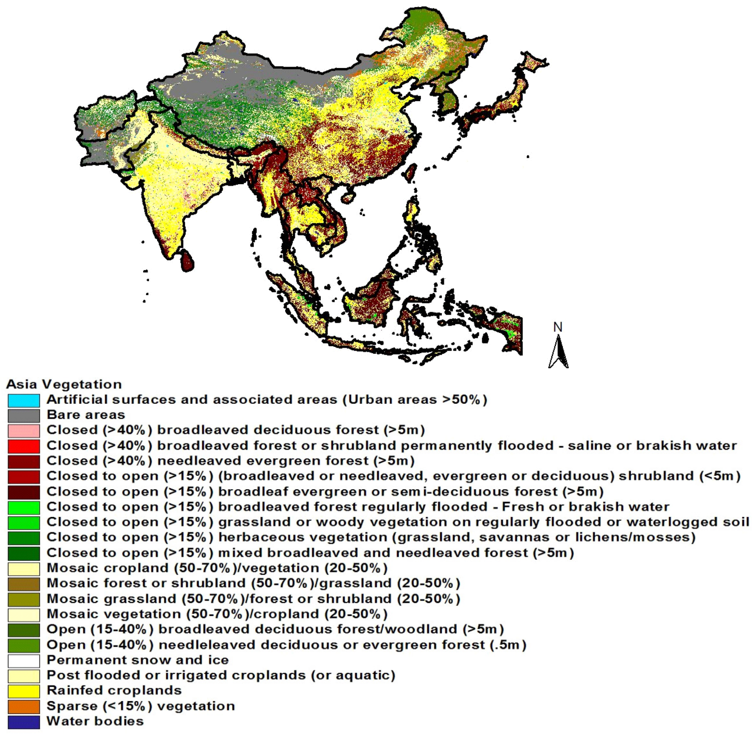

Fig. 8 MERIS-derived (300m) vegetation map of the Asian region.

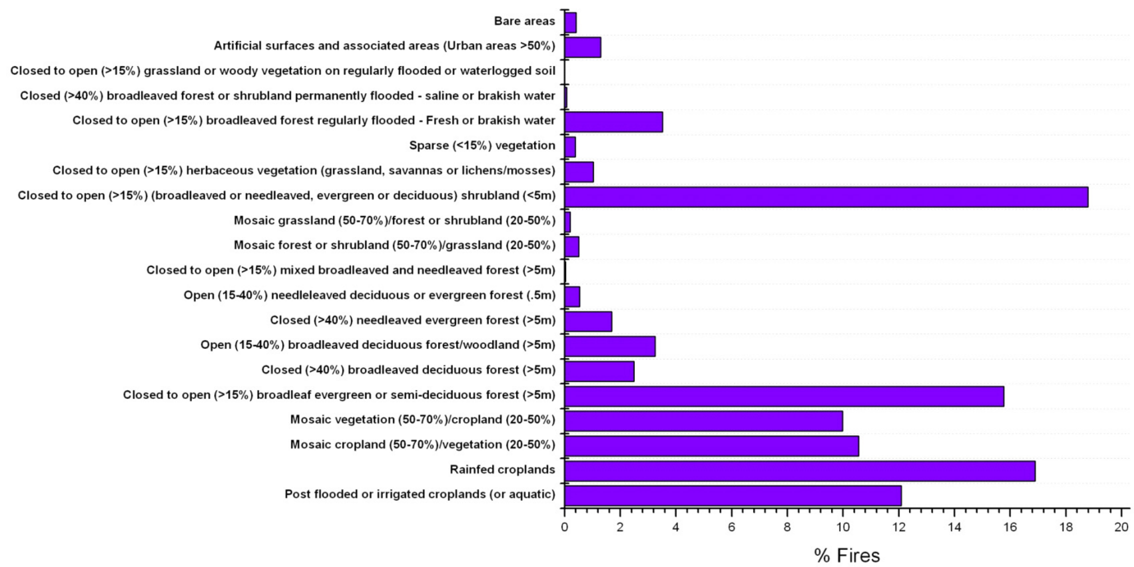

Fig. 9 Percentages of fire occurrences in various vegetation categories.

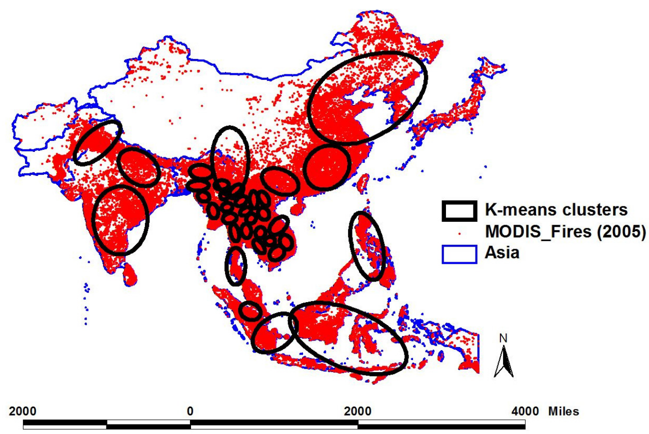

Fig.10 Fire clusters in the Asian region for the year 2005. The K-means algorithm has been used to detect the fire clusters and the hotspot areas in the region.

agricultural residue burning. The hotspot clusters of fire events identified in this study may warrant further attention to assess the relationship between fires, environmental factors and risk.

The new knowledge on fire hotspots delineated in this study can be used in a variety of ways, such as exploring why fires are clustered and assessing the underlying causative factors including fire-vegetation relationships, fire-pollutant-aerosol interactions, etc. Hotspots identified at the provincial scale can help local governmental authorities to intensify their remedial measures and develop future strategies for more effective fire control. Further, as MODIS active fires can be accessed at specific lat/longitudes, such information can be used for fire management and mitigation options.

4. Satellite Observational Needs and Priorities for Improved Fire Research in the Asian Region

In this section, we identify some of the important needs and priorities useful for advancing fire research in the Asian region.

4.1 Algorithm development, calibration and validation

In tropical systems, fires have strong diurnal and seasonal cycles (Goldammer & Price, 1998; Giglio, 2007). Geostationary systems provide the best opportunity for capturing the diurnal cycle of fire activities; however, traditionally they have had a poor spatial resolution. In contrast, polar orbiters have a higher spatial resolution, but provide a limited sampling of the diurnal cycle of fire activity. Thus, integrating geostationary and polar satellite data for effective fire monitoring should be explored through data fusion algorithms (Li & Roy, 2000).

As indicated earlier, several remote sensing products of fire counts, burned areas and fire radiative energy are available to the Asian fire research community, each with its own potentials and certain limitations. Error sources include detection bias, false alarm bias, cloud cover bias, sampling and seasonal error bias, etc. (Giglio, 2007). Although some of the recent satellites such as MODIS under ideal conditions (free of clouds, smoke and sun glint) can detect fire sizes of less than 50m^2 (although the foot print size of such a fire is 1 km^2), such conditions seldom exist in tropical regions, most importantly in Asia. Cloud coverage in tropical areas can have a pronounced effect, limiting fire detection. The impact of cloud obscuration on the detection of active fires in tropical Amazonia has been well documented and is suggested to account for an omission rate of approximately 11% of all fires imaged by coarse resolution sensors (Schroeder *et al.*, 2008). In addition, areas of cloud shadow and semitransparent clouds in tropical areas are also inferred to affect the thermal properties of the surface, thereby potentially enhancing their impact beyond the 11% estimate produced for the active fire data. Changes in the thermal contrast between adjacent areas with different vegetation cover conditions can also influence commission errors (Shroeder *et al.*, 2008). These factors may also impact the fire radiative power retrieved from satellite active fire detections (Roberts & Wooster, 2008).

Understorey burning in tropical forests of the Asian region is another issue. For example, most of the fires in the forested regions of India were reported to be subsurface fires, with burning of litter rather than crown fires (Bahuguna & Upadhyay, 2002; Saha, 2002). Accurate identification of such fires may be difficult. In such cases, burn scar identification requires very high resolution data (Li & Roy, 2000) and improved algorithms (Morton *et al.*, 2011). In addition to those identified above, other local factors may hinder their detection. For example, agricultural fires are short-lived and monitoring them requires satellites with high revisit cycles. Further, due to the small field sizes (less than five acres), validating both the active fires as well as burned areas seems a challenge.

To address these issues on a priority basis, local researchers can aid in identifying product limitations, following extensive validation against ground-truth data as well as inter-comparison of algorithms, focusing on individual ecosystems and then extending to larger biomes. In short, the above issues clearly suggest the need for regionally fine-tuned algorithms for improving the accuracy of active fire and burned area products.

4.2 International network of fire validation sites

There is a need for establishing a network of fire validation sites in diverse ecosystems, including agricultural systems, to develop and to assess algorithm sensitivities to different fire regimes in the Asian region.

4.3 Ground based data

There is a strong need for collection of ground-based data on fire characteristics through field-based campaigns to include fuel loads, fuel moisture content, combustion completeness, emission factors, etc., as they vary based on the ecosystem type, local conditions and meteorology. Including this variability may improve trace gas and aerosol emission calculations and the resulting climate impacts (van Der Werf *et al.*, 2006).

4.4 Data availability and accessibility

There is a clear need for space agencies and national governments to increase their international coordination activities with respect to sharing locally available data on land use/cover, meteorology, fire observations, vegetation, etc. (Justice *et al.*, 2003). In the Asian region, several countries (India, China, Japan, Singapore, Malaysia, etc.) over a period of years have already developed robust remote sensing laboratories to acquire and process data and develop products. Coordination amongst different Asian countries is needed to make the data freely available and accessible to the public through a common platform. Globally, satellite observations are currently being coordinated through the Coordination Group for Meteorological Satellites (CGMS) and the Committee on Earth Observation Satellites (CEOS). Input to space agencies from the scientific and satellite data user community is being coordinated through the GOFC-GOLD Program and associated regional fire networks. The Global Fire Monitoring Center, Germany, has taken the lead in coordinating the broader needs of the fire monitoring community in the context of the United Nations International Strategy for Disaster Reduction (UNISDR) Global Wildland Fire Network. Validation protocols for satellite fire products and standards for validation reporting are being developed by the CEOS Land Product Validation subgroup.

4.5 Data assimilation system for early warning of fires

For developing a robust early warning system relating to fire danger, including post-fire impacts, there is a strong need for developing a data assimilation system for the Asian region, which can ingest both ground-based and remotely-sensed fire information. Fire danger rating is a means of quantifying the potential or ability of a fire to start, spread and cause damage (Merrill & Alexander, 1987). Formal Fire Danger Rating Systems (FDRS) have been in development in Canada, Australia and the United States for about 75 years (Stocks *et al.* 1989). In Indonesia and Malaysia, a fire danger rating system has been developed, involving the Canadian International Development Agency (CIDA), the Canadian Forest Service (CFS) and a number of local government agencies and universities (de Groot *et al.*, 2006). The Canadian Forest Fire Danger Rating System (Stocks *et al.* 1989) has two subsystems that are currently used operationally: the Canadian Forest Fire Weather Index (FWI) System (Van Wagner, 1987) and the Canadian Forest Fire Behavior Prediction (FBP) System (Forestry Canada Fire Danger Group, 1992). Risk, weather, fuels, and topography provide the necessary inputs to predict fire weather, fire occurrences and fire behavior. Fuel moisture models are currently being developed for a range of Canadian forest types. Together, these systems can predict the potential fire danger within the forest. To develop and extend such a system for the entire Asian region, there is a strong need for the individual countries to form a coalition and share data on a common platform for building a data assimilation system useful for detecting fire danger. Such a system can provide a valuable resource for organizing and integrating scientific knowledge for addressing fire and transboundary air pollution problems in the region. In addition to the above, to meet local and regional user needs, data management issues, including data sharing policies, should be evaluated and refined as necessary.

Several of the above needs can be addressed via expert interaction through international programs, such as GOFC-GOLD, which has been in existence for almost fourteen years. This program's details, goals and implementation strategies are highlighted below, and we call for increased participation of Asian researchers through networking with the GOFC program.

5. GOFC-GOLD Fire

GOFC-GOLD is an organization focused on international coordination of enhanced Earth observations. Its overall aim is to improve the quality and availability of space-based and *in-situ* observations at regional and global scales and to encourage the production of appropriate, timely and validated information products. Originally developed as a pilot project by the Committee on Earth Observation Satellites (CEOS) during 1997 as part of their Integrated Global Observing Strategy (Ahern *et al.*, 1998), GOFC-GOLD is now a panel of the Global Terrestrial Observing System (GTOS). The essence of the GOFC-GOLD implementation strategy is to develop and demonstrate operational monitoring at regional and global scales by conducting pilot projects and developing prototype products under three different themes: land cover characterization and change, fire mapping and monitoring, and biophysical processes (Townshend *et al.*, 2004).

The GOFC- GOLD Fire Mapping and Monitoring Implementation Team (Fire IT) is comprised of experts from national and international space agencies, governmental and non-governmental environmental organizations, and universities. Fire IT aims to refine and articulate international observation requirements and encourage the use of satellite-derived fire products and information from existing and planned systems for global change research, fire management and policy decision-making. This includes identifying the observation priorities and needs of the fire community, such as facilitation of collaborative research in recognized priority areas, periodically identifying critical observation gaps (Justice *et al.*, 2003), promoting the use of space-borne assets for fire research, provision and validation of fire products, and improving data distribution and capacity building. The current GOFC-Fire IT goals and sub-tasks are highlighted in Fig. 11.

More specifically, the function of Fire IT includes:

- Developing a connected fire observation community with a common agenda for advancing community goals.
- Refining and articulating the international requirements for fire related observations.
- Promoting free and open provision of high-quality derived-data fire products to meet both science and application user needs.
- Increasing access to and encouraging best use of fire products from existing (and future) satellite observing systems, for fire management, policy decision-making and global change research.
- Promoting the provision of long-term, systematic satellite observations necessary for the production of the full suite of recommended fire products and the development of new technologies for fire management.

Fire IT is actively pursuing these goals and functions

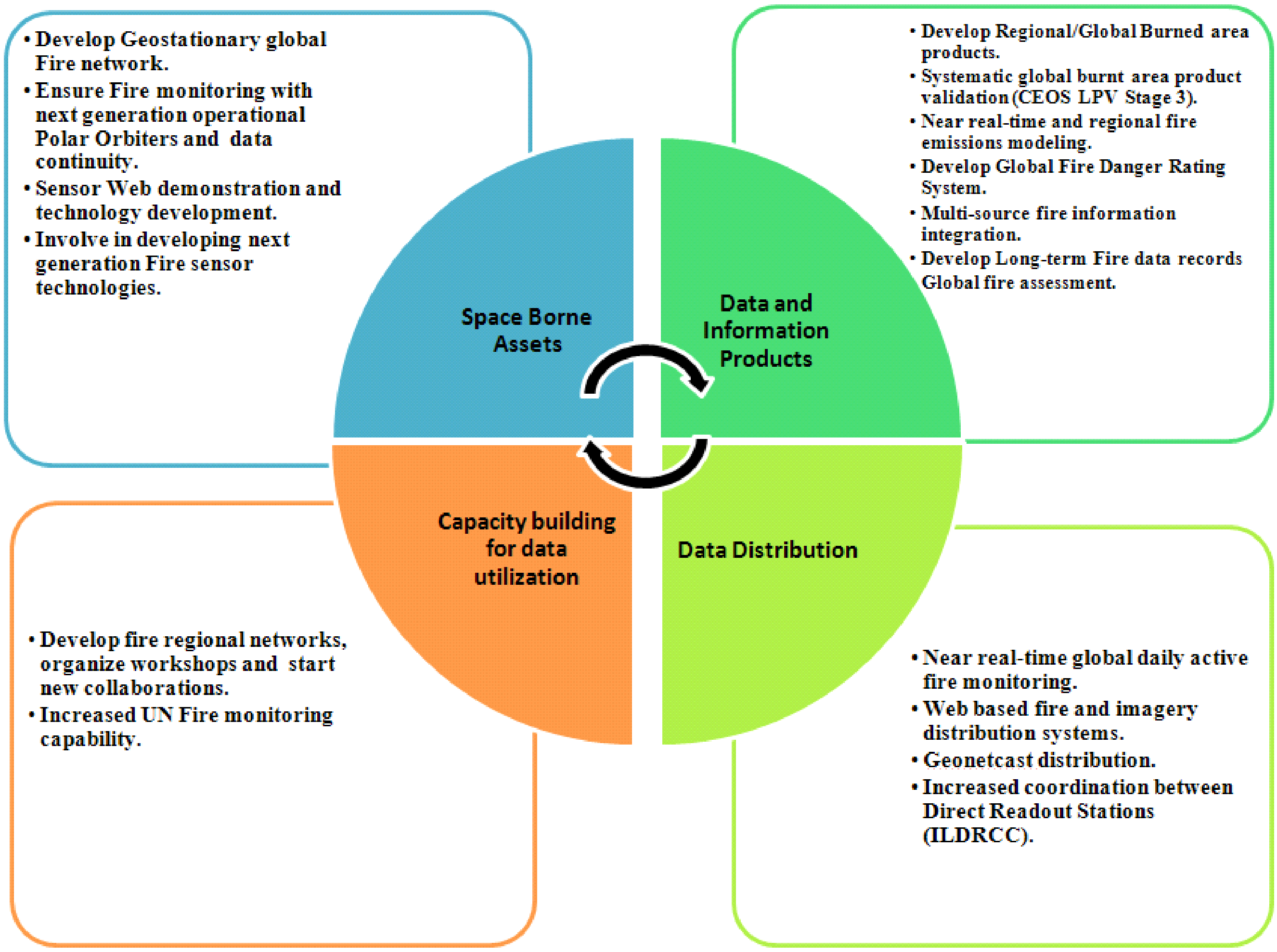

Fig. 11 GOFC-Fire IT goals and strategies.

through international and national contributory projects involving regional experts and strategic partnerships with the relevant international organizations. Currently, experts from several regional networks are involved with the GOFC-Fire IT program, covering diverse regions such as the Amazon, northern Eurasia, Central Asia, central Africa and West Africa. Also included are southern Africa, western Africa, Latin America, Southeast Asia and India. GOFC-Fire IT is continuously expanding its outreach activities all over the world and strongly welcomes the participation and interaction of Asian researchers.

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