The relationships between biomass burning, land-cover/use change, and the distribution of carbonaceous aerosols in mainland Southeast Asia: A review and synthesis

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Biomass burning is a major source of black carbon aerosols. These aerosols have negative human health impacts and can affect the radiation budget and climate directly and indirectly. Uncertainty regarding the contribution of biomass burning to the concentration of aerosols is higher in Southeast Asia than in some other regions of substantial biomass burning because of other sources of pollution such as significant fossil fuel combustion. The slash-and-burn agricultural tradition is still evident in the region. Significant expansion of cash-crop production is also associated with biomass burning, as is the seasonal burning of crop residue. The effects of such land-use processes extend into the atmosphere, and localized events have regional and global implications for air pollution-related health effects and climate. This paper synthesizes the issue of biomass burning and aerosols in the context of land-use practices in Southeast Asia, and makes suggestions of how to use available data sources in an integrated analysis.
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1. Introduction

A recent research thrust in the global change community has been to measure, model and understand coupled human-environment systems. It is increasingly recognized that social and physical processes must be conceptualized and studied as an integrated system. Land-atmosphere relationships represent one major class of such integrated systems. Knowledge of these relationships is more developed for some phenomena than others. Large datasets exist on the relationship between land-use change and carbon dioxide (for a summary, see IPCC, 2001). On the other hand, the information on aerosol production resulting from land-use change is more limited, including how such changes will affect aerosol transportation patterns, precipitation states and efficiency. Because aerosols can both scatter and absorb radiation, their impact on climate is complex, and often uncertain (IPCC, 2001). Black carbon particulates, released by both biomass burning and fossil fuel combustion, may lead to increased warming, as more ultraviolet radiation is absorbed than scattered by these particulates (Jacobson, 2001). In addition, biomass burning has negative implications for human health. Epidemiological studies indicate that the health effects of outdoor air pollution may be more severe in Asia than in Europe or North America due to the magnitude of the air pollution, the amount of exposure to pollution and the underlying health status of the population. Fuel combustion is the largest contributor to total air pollution, but biomass burning (in- and outdoors) is still a significant contributor to overall pollution levels, especially in poorer regions (HEI, 2004).

Studies have shown that the absorption of light by aerosols is due to high atmospheric concentrations of black carbon. Black carbon particulates last in the atmosphere only a short time, compared to greenhouse gases that can last for several decades, yet the immediate heating effects of radiative absorption can be much greater (Bond et al., 2004). Aerosols generated by biomass burning are estimated to constitute 25% of all aerosols in the Southern Hemisphere, and 13% of all aerosols globally, and the percentage of biomass burning emissions that are black carbon (as opposed to organic carbon) are estimated to be 9.4% and 9.5% , respectively (IPCC, 2001: 296, 297; Authors' calculations).

The Global Land Project (GLP, 2005) has identified the need to understand better the impact of land-use/cover change on the atmosphere. In particular, there is a need to quantify the impact of carbonaceous aerosol emissions that result from spatial processes operating at a *local* scale (e.g., biomass burning) on the atmospheric concentration of aerosols over a *region*. Previous research has considered the land-use change/aerosol relationship at a single scale, either by quantifying the amount of emissions from a local source or by studying the aerosol distribution over a large region without considering individual aerosol sources. In order to combat undesirable environmental and health effects from aerosols, a better understanding of local-regional land use/aerosol relationships is required. Knowledge about expected changes in the patterns and types of land-use patterns associated with biomass burning will also be key for policy.

Biomass burning releases several types of particles including organic carbon, black carbon, and volatile organic compounds (Streets et al., 2003). Black carbon (or elemental carbon) is the primary absorbing aerosol in the atmosphere. Sources of carbonaceous aerosols include fossil fuel burning, domestic burning (cooking and heating), and the burning of vegetation and agricultural residue (Kanakidou et al., 2004). Black carbon affects cloud formation and increases solar heating (Uno et al., 2003). More generally, aerosol emissions can affect large portions of the world, due to long-range transport (Andreae and Merlet, 2001). Incomplete knowledge of the extent and pattern of aerosol forcing is due in part to uncertainties in matching the distribution of aerosols to likely sources (Yu et al., 2006). Streets et al. (2003) report that the emissions of carbonaceous aerosols are largely uncertain in Southeast Asia, because there is limited information available regarding the pattern of biomass burning practices and fossil fuel emissions (e.g., through increased use of automobiles). The emission rates and transport process of black carbon over Southeast Asia also are not well understood, and are a key research priority given high levels of pollution in this area (Ramanathan et al., 2001).

To assess the atmospheric impact of biomass burning, accurate data on aerosol emissions from fires is needed. Regional scale studies should be a key research priority in order to reconcile some of the uncertainties in global models (Andreae and Merlet, 2001). In Southeast Asia, the estimation of aerosol emissions from biomass burning is confounded by the significant fossil fuel combustion and industrial pollution; therefore, analyses linking carbonaceous aerosols concentrations to the spatial and temporal patterns of biomass burning would reduce these uncertainties (Chin et al., 2002).

In this paper, we synthesize prior research concerning the relationships between fire, biomass burning and land-cover change in Southeast Asia. This paper reviews critical research needs for the land-use community in order to contribute to ongoing efforts to conceptualize land-atmosphere interactions as one example of a linked human-environment system. We also survey current literature regarding land-use practices in the study region as they relate to likely changes in fire trends. More generally, the relationship between biomass burning and carbonaceous aerosols is insightful as an example of critical land-atmosphere interactions. Finally, we discuss the use of available tools and data sources as a means to analyze biomass burning-aerosol relationships on a regional scale.

2. Land-atmosphere interactions

Land-use practices have a range of consequences for the earth system. One can broadly characterize land-atmosphere interactions as those processes by which terrestrial ecosystems, affecting and affected by climate change, are linked to chemical and physical fluxes in trace gases and particulates. Substantial research has been conducted over the last several decades to link human activity to carbon-cycle processes, such as changes in carbon uptake and storage resulting from deforestation. Relatively less is known about the relationship between land use and aerosols, but Pielke et al. (2002) suggest that surface-energy budget effects on climate may be more important than the carbon-cycle effects, and they indicate that more research is needed to quantify the impact of human disturbance of the Earth's surface-energy budget. The ultimate impact from human activity on atmospheric composition and radiative balance will be seen in a variety of physical and ecological processes (Bond et al., 2004).

Changes in land management decisions affect the biogeochemistry of the atmosphere. Alterations in the chemical composition of the atmosphere in turn have a direct impact on ecosystem dynamics. Changes in biogeochemical cycling can alter atmospheric composition, radiative forcing, evapotranspiration and precipitation, and the cycling of water, carbon and other nutrients (GLP, 2005). Aerosols can have a variety of direct and indirect effects on the hydrological cycle and on climate. Aerosols thus can both scatter and absorb radiative energy, resulting in either a local heating or cooling effect. Absorption of radiative energy can further impede cloud formation (Andreae and Merlet, 2001). In addition, aerosol impacts can be amplified by positive feedbacks. Aerosols are removed from the atmosphere by precipitation, but if precipitation is suppressed by aerosols, they remain in the atmosphere longer, furthering their impact. Drier conditions from suppressed aerosols also increase dust and smoke (from drier vegetation). These direct and indirect effects can lead to microclimatic changes and, cumulatively, can significantly disrupt the regional hydrological cycle (Ramanathan et al., 2001). Finally, biomass burning and the associated release of aerosols into the atmosphere have potentially serious effects on both the locations where the pollution is created and the locations to which it is transported (Pfister et al., 2005).

Studying the extent and pattern of aerosols is an empirically challenging task. One of the difficulties in assessing the land-use/cover change - black carbon aerosol relationship is determining the relative contributions of biomass burning versus fossil fuel combustion on the regional atmospheric concentrations of carbonaceous aerosols (Streets et al., 2003). Several factors influence the extent and severity of biomass burning, including density of the vegetation, humidity, temperature and wind speed (Schultz, 2002). Numerical transport models of carbonaceous aerosols have demonstrated key uncertainties in sources and sinks of black carbon (Uno et al., 2003). Aerosols differ from greenhouse gases, which are distributed uniformly, in that they generally remain in the atmosphere for only a short time, and thus large spatial and temporal variations in their concentration are evident (Ramanathan et al., 2001). To understand the spatial and temporal patterns of aerosols, it is necessary to develop spatial and temporal emission profiles relating these patterns to land-use processes.

The land-atmosphere system is vulnerable to human perturbation. Shifting agricultural systems can lead to profound changes in aerosol emissions. For example, a change from shifting cultivation to more permanent, cash crop-oriented production will cause a shift in the locations, amount and type of biomass burning, which will have a host of local and regional implications. As shifting cultivation declines, the burning practices associated with the clearing of fallow fields will also decrease. Cash crop expansion can lead to increased burning of forests, however, as new land is cleared for permanent cultivation. In addition, the burning of agricultural residue may increase. Various land-use practices have different expected emission rates, but it remains an empirical question what the exact amount and spatial and temporal pattern of these emission rates will be on an intraregional scale (Streets et al., 2003). Finally, because aerosols are highly mobile, and complex physical and chemical interactions among particulates can occur in the atmosphere, changes in biomass burning associated with evolving land-use systems can also interact with other sources of aerosols (including the burning of fossil fuels). As a primary example, while it is clear that the brown haze over Southeast Asia and the Indian Ocean has significant implications for the regional energy balance, it is unclear to what degree biomass burning and fuel combustion are responsible for the haze (Uno et al., 2003).

3. Regional context of Southeast Asia

Mainland, or peninsular, Southeast Asia, approximately spans from 93° to 109° E, and from 10° to 25° N and includes five major countries (Burma, Thailand, Laos, Cambodia, and Vietnam). Except for a few major deltas and narrow coastal plains, the entire region consists of steep slopes and highlands that form a fragmented mountainous and semi-mountainous terrain. Most of the area is strongly influenced by monsoon winds that result in a wet season (from May to October) when southeast winds from the Indian Ocean generate heavy rainfall and severe flooding, and a relative dry season between November and March (typically less than four inches rainfall per month). Under such a climate, tropical evergreen and deciduous forests have developed (Kummer, 2000), and a variety of tree species (e.g., teak and dipterocarps) with high commercial value in international markets are abundant in these forests.

Processes of land-cover change in mainland Southeast Asia exhibit many characteristics of interest to the land-use community. Though the diversity of regional forests is regarded as a unique characteristic of mainland Southeast Asia, the original forests have been largely lost to other land uses during the past century. In all portions of the study area, deforestation is a major concern across all scales, from the local village to the national government. It is possible to identify a number of factors that contribute to the deforestation that has taken place in this area. However, human causes (especially those related to economic activities) have been considered as the major driver (see Kummer and Turner II, 1994; Kummer, 2000).

Shifting cultivation, market-oriented production, and logging (both legal and illegal) are generally regarded as the leading causes of forest degradation and removal. These trends have become especially important factors over the past two decades. The basic agricultural activities in this area can be placed into three types: sawah (wet rice cultivation) is normally associated with lowlanders who migrate to forested areas; shifting (slash and burn, or swidden) cultivation is typically performed in upland and causes a great number of fires; and there have been dramatic increases in the production of cash crops (e.g., coffee, rubber, and cashews). Besides agricultural factors, commercial logging has also played an active role, effectively converting original forests to grasslands in many areas.

Table 1 summarizes trends in forest cover between 1990 and 2000 for each country in the study area. Loss of forested area is evident in all countries in the study area between 1990 and 2000, except for Vietnam, which gained forested area in this time period. However, Vietnam has also dramatically increased the production of coffee over the last decade, and some of the forest statistics may reflect coffee canopy. Table 2 and Figure 1 present trends in crop production, for selected cash crops (such as coffee and cashews), as well as staples like rice and cassava (cassava can also be produced for animal feed). There are interesting temporal trends, as well as trends across countries. Rice comprised the largest share of output in all countries, but only by a small majority in Thailand. In terms of percent change in output, there was nearly an 800% increase in coffee production in Vietnam between 1990 and 2000, although the rate of increase slowed down by 2004. Coffee also increased considerably in Laos. While there were considerable regional variations, other significant increases included sugar cane and cashews (FAO, 2007a).

4. Land-use systems and biomass burning in Southeast Asia

Knowledge about land-practices and biomass burning is crucial to understanding aerosol trends. In this section, we review and synthesize recent research on the land-use context of biomass burning in Southeast Asia. There are several interesting dimensions across which the variations in fire and land-use practice are evident, including upland/lowland variations, important policy changes, and uneven, yet overall increasing, cash-crop production.

Land-cover change achieved through fire occurrence has social and environmental consequences as a result of carbonaceous aerosol emissions. Slash-and-burn agricultural practices in upland areas in Southeast Asia are a significant fixture of the landscape, particularly since the 1960s. It is short-sighted to assume that the distribution of poverty and population density irrevocably lead to the destruction of forests (Lambin et al., 2001); such land use systems can be stable (Fox et al., 2000) or even possibly sustainable in terms of the global carbon cycle. On the other hand, the impact of the black carbon aerosols generated by biomass burning will likely be increasingly important in terms of regional and global climate change, and effective national and international environmental policy must incorporate these effects (IPCC, 1996). To understand how biomass burning fits into land-use systems, a number of factors must be considered.

In the countries which compose mainland Southeast Asia there are a number of human-induced and natural causes for fire occurrence. Biomass burning is directly associated with land use in subsistence farming, cash cropping, and logging. Certain agricultural activities, in particular shifting cultivation, have a high potential for the generation of fire, and have been most extensively studied. Unfortunately, the relationships between cash cropping, logging and fire, while becoming increasingly important, are a less developed body of knowledge in Southeast Asia.

4.1 Shifting cultivation

The traditional process of shifting cultivation (also known as slash-and-burn or swidden agriculture) is characterized by a short cultivation period of one to three years followed by a long fallow period of up to twenty years in which the land is able to regenerate for the next clearing and cropping cycle (Ducourtieux et al., 2006).

The patterns of agricultural activity in large part correspond to the terrain. Lowland areas are the location of the majority of the population of these countries (Thomas, 2003) and have been continuously settled for hundreds of years. Lowland sections generally contain areas of continuous cultivation, particularly along the region's rivers, and the coastal lowlands are where most plantation agriculture can be found.

The settlement and farming patterns are dramatically different in the upland, mountainous areas. Upland areas tend to be where shifting cultivation is found (DeLang, 2005). The uplands are sparsely settled in comparison to the lowlands. The terrain is much more extreme, with steep slopes and heavy forest cover (Delang, 2006; Rumpel et al., 2006; Leisz et al., 2005; Cairns and Garrity, 1999). The people practicing shifting cultivation are often ethnic minorities (Rerkasem and Rerkasem, 1995) who have a cultural tradition dramatically different from lowland area dwellers (Bottomley, 2002; DeLang 2005). More traditional village areas are found in the uplands, often practicing subsistence farming much in a similar manner as their ancestors did hundreds or even thousands of years ago (Fox and Vogler, 2005).

The upland/lowland dichotomy cannot fully explain the relative abundance of shifting cultivation or cash crop production in all locations, as Douangsavanh et al. (2003) demonstrated in the Lao PDR. Throughout the Southeast Asian region, agricultural practices are observably shifting in intensity and types of crop grown (Giri et al., 2003). Shifting cultivation remains a primary activity for large numbers of people in the countries of Cambodia and Burma, while the prevalence of this type of agriculture is experiencing decreases in the countries of Laos and Vietnam, along with an accompanying increase in the prevalence of cash crop production. Thailand has the longest experience with cash crop production. Vietnam and Thailand are leading the move into market-oriented crop production, but at the same time, within these countries, areas can be found which are still practicing subsistence shifting cultivation, as are places that are just beginning to be reached by roads and markets. Due to this varied spatial distribution of these quite different crop production systems, it is difficult to make generalizations about the future trajectory of farming and consequent deforestation in the region.

4.2 Drivers of land-use change

A number of factors are bringing about changes in the nature of traditional shifting cultivation, leading to increased intensification of production. Individual cultivators may be increasing the number of years in which a plot of land is under cultivation and decreasing the time period in which the land is allowed to lie fallow (Rasul and Thapa, 2003). There are evident differences, reflected in the variation of farming practices, between and within countries in Southeast Asia. Underlying these differences are population dynamics, economic change, and political and institutional reform. These factors explain the major differences in upland production practices between these countries.

Population trends and land-use change in the region come together in interesting, yet complex ways. Urbanization is a dominant process in the region, yet the preponderance of the population is rural: the rural population across the region constituted 76% of total population in 1990, and 72% of total population in 2005 (United Nations Population Division, 2005). Templeton and Scherr (1999) summarize an exhaustive literature studying population density and land-use change in mountainous regions, and conclude that local population growth is not necessarily associated with environmental decline. Rather, it may spur more intensive land-use practices, consistent with Boserup's (1965) predictions, including less extensive cultivation, associated with the movement from slash-and-burn to permanent crop cultivation. To the degree that population density increases are associated with increased competition for land relative to labor availability, land conservation measures may be adopted. While population densities are increasing, they are not increasing in such great numbers as to be the primary cause of the intensification of shifting cultivation. As Rasul and Thapa (2003) highlight in the case of Laos, while the country's population pressure has been increasing at the rate of two percent a year, the gross population density is still less than 20 persons 20 km^{-1} (Rasul and Thapa, 2003: 501). Population growth rate is an important statistic when comparing locations at the national level, but becomes less meaningful at the sub-national level. Population growth is happening most rapidly in urban areas, while at the subnational scale, the uplands are still relatively sparsely populated.

More importantly, continued shifting cultivation is most likely in the more remote areas. Market integration encourages the transition from shifting cultivation to production of cash crops

(Thongmanivong et al., 2005). Infrastructure, particularly access to roads and markets is a key component of the movement to more permanent cultivation. Markets are not easily accessible in much of this region (Pandey and van Minh, 1998), and the lack of roads and other infrastructure precludes the production of cash crops for markets in large portions of mainland Southeast Asia. By these criteria, much of Cambodia, Burma, and Laos can be considered remote (Roder et al., 1997; Hang and Suzuki, 2005). Thailand and Vietnam, however, are continuing to increase markets and access for farmers even in more remote locales (Pandey and van Minh, 1998; Rasul and Thapa, 2003). In addition to physical infrastructure, financial infrastructure is also important. Lack of access to credit prevents the necessary investments in technology required for cash crop production. Subsistence shifting cultivators are poor and do not have the financial assets to introduce technology to farming techniques, which is needed in the production of cash crops for markets (Vosti and Witcover, 1996). Therefore, availability of credit is necessary for this change (Rasul and Thapa, 2003).

Government policies also affect upland shifting cultivation. Because shifting cultivation is seen as an environmentally destructive activity (Ducourtieux et al., 2006), national governments are attempting to move shifting cultivators into sedentary farming in many locations. Shifting cultivation is also blamed for the high rates of deforestation throughout the region, even though significant amounts of legal and illegal logging are also occurring (Phat et al., 2004; Leimgruber et al., 2005; Brady, 1996). Governments want to reduce the mobility of the upland farmers and encourage them to plant and invest in the land (Castella et al., 2006).

An overarching factor underlying the transition from shifting cultivation to sedentary cash crop production is land relations (Ducourtieux et al., 2005). Insecure land rights can discourage farmers from investing in the land, as there is always a possibility that they could be forced from it (Rasul and Thapa, 2003; Harwood, 1996). Land has been traditionally seen as a free resource to be used in absence of land ownership (Rerkasem and Rerkasem, 1995) so governing bodies must address this issue to be successful in encouraging cash crop production. In Thailand and Vietnam, for example, land rights policies are becoming more prevalent. These policies encourage upland farmers to move from subsistence shifting cultivation to economic sedentary farming.

Forest use policies are another way in which governments attempt to halt the practice of shifting cultivation. In many areas, there has traditionally been no enforcement of forest protection, leaving virtually no restrictions to access of land (Rasul and Thapa, 2003). However, this situation is changing (Rerkasem and Rerkasem, 1995). In Laos, for example, the government has instituted the Land-Forest Allocation Programme in hopes of stopping shifting cultivation in forest areas by removing people from upland areas (Rigg, 2006; Rasul and Thapa, 2003). Thailand's Royal Forest Department has also re-classified forest lands into conservation areas for similar reasons (Buch-Hansen, 2003; Rasul and Thapa, 2003). Poor enforcement of these policies, however, has limited their effectiveness.

4.3 Trends in market-oriented agriculture

Cash crop production is characterized by intensive sedentary land use, use of technology, *de facto* or *de jure* land rights, availability of credit, infrastructure, and market access. Shifting cultivation is generally found in areas that do not have these opportunities. All of these issues must be jointly considered, as they reinforce one another. The presence of markets is a major factor. Without nearby markets, the transportation costs are too high for small farmers. Cash crops require technology to produce, and it is more likely that subsistence farmers will be pushed out by larger plantation-scale farming. These issues are of particular importance in Laos, Cambodia, and Burma. As Ducortieux (2006) concludes, the transition from shifting cultivation to cash crop production can be a very difficult transition for subsistence farmers with much potential for failure.

Overall, landscapes are increasingly dynamic. Fox and Vogler (2005) note that the major agricultural land changes in a study area encompassing parts of Cambodia, Vietnam, and Laos was a decrease in shifting cultivation and an increase in village and plantation areas, including rubber, palm oil, plantation tree crops, and paddy rice. However, the simple transition from subsistence shifting cultivation to cash crop production does not end the use of fire in agricultural production. Land must still be cleared to begin sedentary agricultural practices. As Entwisle et al. (2005) learned in a study of Nang Rong, Thailand, much of the high elevation forest was removed for farming cassava to export as animal feed after the Second World War. This type of activity would result in an initially large amount of fire, followed by few fire episodes as the land will be continuously cultivated thereafter.

4.4 Implications of land-use change

In terms of aerosol emissions, there is not a simple answer regarding the "correct" mixture of land-uses and burning practices. Many portions of the Southeast Asia study area are poised to make transitions which may dramatically shift land use throughout the upland areas, in particular the move from subsistence agriculture to market-oriented agriculture. As this occurs, the land use of the region will have a different composition, with sedentary farming becoming the dominant activity. The implications of this transition on biomass burning may be that periodic burning practices will be diminished, but forest clearing for new fields and the burning of agricultural residue will increase. Perhaps too much empirical focus has been placed on shifting cultivators as the primary agents of negative environmental change, though shifting systems were relatively stable in terms of land-cover impact for many decades (Fox et al., 2000). Much greater uncertainty surrounds the newer land-use practices evident in the region. While cash crop production is also associated with fire occurrence, it will likely have a lower rate of fire in comparison with shifting cultivation, provided that the sedentary farmers do not use fire each year to clear previous years' residue. There do not appear to be any studies on the use of fire in plantation agriculture in the region. Regardless, this use of fire releases fewer emissions per area than the practice of shifting cultivation, where generally a greater volume of vegetation per area is burned in order to gain additional nutrients with which to fertilize the soil. Black carbon emission estimates for 2000 report the highest emissions for crop residue (0.69 g/km), then forest (0.56-0.66), with savanna/grassland significantly lower (0.48) (Streets et al. 2003: 30-6). Across Asia it is estimated that the ratio of biomass burned in Tg from crop residue to forest is about 0.75 (Streets et al. 2003: 30-4), although the likely changes in volume burned for each of those categories remains uncertain.

5. Data and Tools for an Integrated Analysis

Because information regarding the spatial and temporal patterns of burning, and the type and volume of vegetation burned is scarce, uncertainty remains regarding the contribution of biomass burning to aerosols. Uncertainty about this relationship is particularly acute in Southeast Asia, as compared to Africa or South America because there are a greater variety of activities generating the emissions of carbon particulates (Chin et al., 2003). More creative use of available data and particularly statistical summaries of space-time associations may shed greater light on the magnitude of the contribution of biomass burning even given concomitantly increasing levels of background pollution.

While information regarding the spatial and temporal distribution of fire is critical, it is not sufficient to estimate the magnitude of biomass burning. The relationship between biomass burning and aerosol emission is as follows. The amount of biomass burned in a fire is given by:

$$M_{biomass} = A * B * \alpha * \beta, \quad (1)$$

where A is the burned area, B is the biomass density, and α and β are the fractions of below ground and above ground biomass burned, respectively (Seiler and Crutzen, 1980). Then, in turn, the amount of matter emitted into the atmosphere is as follows:

$$M_x = EF_x * M_{biomass} \quad (2)$$

where M_x is the mass of the particulate type x emitted into the atmosphere, given the emissions factor (or the amount of pollution discharged) for that species EF_x and the estimated amount of biomass burned M_{biomass} (Ichoku and Kaufman, 2005). Therefore, in order to produce reliable estimates of the impact of fire activity on atmospheric concentrations of black carbon, information is needed on the amount of biomass released from a fire, as a function of vegetation and the size and intensity of the fire, and the expected amount of mass actually released into the air.

Reliable ground-based estimates of fire activity are extremely limited (Duncan et al., 2003; Giglio et al., 2003). Because of the large spatial and temporal variability of aerosols, satellite-based measurement is necessary for reliable information regarding their distribution (Ramanathan et al., 2001), and the use of fire products to empirically monitor the distribution of biomass-burning activity is becoming more widespread (Giglio et al., 2006). Remotely-sensed data for measuring carbonaceous aerosols are additionally desirable because atmospheric circulation processes produce regional impacts of biomass-burning events (Uno et al., 2003).

Because aerosols are highly mobile, their position in the atmosphere can impact the accuracy of a particular measurement approach. For example, ground-based measurement may be unduly influenced by smoldering fires whose emissions do not necessarily extend far into the upper layers of the atmosphere; remotely-sensed measurements can in turn overweight those emissions that rise up to higher levels of the atmosphere (Andreae and Merlet, 2001). Thus, it is the case that a combination of data sources, whenever possible, should be used to study fire activity and aerosols (Boschetti et al., 2004). In this section, we discuss the variety of different sources of information that can be used in integrated analyses of atmospheric impacts of land change and biomass burning.

5.1 Data Sources

Large uncertainties remain in the estimates of aerosol forcing due to incomplete knowledge of the physical and chemical properties of aerosols and aerosol-cloud interaction. Reduction of the uncertainties requires the integration of ground-based, aircraft and satellite measurement and techniques (Tanre et al., 1999). Table 3 summarizes several available data sources that have been used in combination to explore fire and aerosol associations. There are significant empirical challenges to be overcome, however, due to problems of temporal and spatial misalignment, missing data, and variations in data quality.

5.1.1 Fire Products

The earliest satellite fire products were developed using data from the Advanced Very High Resolution Radiometer (AVHRR) as part of the National Oceanic and Atmospheric Administration's (NOAA) Satellite Information System and the European Space Agency's World Fire Atlas. Both products use nighttime detection to reduce false positives from glare and other systematic errors more likely in the daytime.

Fire and Thermal Anomalies Product derived from daytime and nighttime data collected using the Moderate Resolution Imaging Spectroradiometer (MODIS), an instrument onboard the Earth Observing System's (EOS) Terra and Aqua Satellites. This product provides the center point of a 1km resolution pixel where a fire has occurred (Justice et al., 2002). A fire pixel does not always correspond to a single fire, but can represent that one or more fires fall within the pixel at time of observation (Giglio et al., 2006). In a given scene, the minimum detectable fire size is a function of many variables, including scan angle, sun position, land surface temperature, cloud cover and the amount of smoke and wind; thus the detection effectiveness varies with these conditions. Errors of commission ("false positives" for fire detection are more likely than omission, or the failure to observe a fire that is occurring) (Justice et al., 2002).

Total burned area is a key component of the emissions equation (2) and therefore area burned is an ideal input to studying the atmospheric effect of biomass burning. However, Boschetti et al. (2004) demonstrated that while the spatial agreement of most of the fire detection products is high, the estimates of burned area vary widely.

5.1.2 Aerosol data

There are several satellite-based aerosol products available. The MODIS product greatly improved over past space-based measurements where reflectance was only measured across only one or two channels. MODIS is able to provide information on aerosol optical thickness, and size parameters (e.g., fine mode fraction). However, the glint mask (sensitivity due to reflection) is a source of systematic error (Tanre et al., 1999). The Multiangle Imaging SpectroRadiometer (MISR) sensor, also onboard the EOS satellites, integrates over nine viewing angles, which enhances the sensitivity to aerosols. MISR Level 2 aerosol data contain a variety of information, including aerosol optical thickness, size and shape of aerosol particles and the Angstrom exponent, and single-scattering albedo. MISR data are available every nine days at 17.6 km resolution. Other satellite aerosol data sources include the European Space Agency's ENVISAT Medium Resolution Imaging Spectrometer, and France's POLarization and Directionality of the Earth's Reflectance.

The Aerosol Robotic Network (AERONET) is a federation of locally owned ground-based radiometers, whose data are centrally archived (Holben et al., 1998). These data are commonly used to validate satellite-based products as well as the outputs from aerosol simulators. However, due to the network's restricted spatial coverage, AERONET data alone is limited in larger-scale analyses.

5.1.3 Biomass burning emissions

Different cash crops require different levels of land clearing. Cardamon, for example, does not require the removal of large trees as it thrives in forest understory (Ducortieux, 2006). Once an area has been cleared, it can be continuously cultivated, but requires large inputs of fertilizers and pesticides, such as cabbage and cut flower production (Savage, 1994; Tungittiplakorn and Dearden, 2002). Giglio et al. (2003) found greater uncertainty with regard to savannah or grassland fire pixels, and fire associated with denser vegetation types. There is relatively less certainty regarding the likely emissions from agricultural fires (such as the burning of residue), as compared to other vegetation types (Andreae and Merlet, 2001).

Estimates are available concerning the magnitude of biomass emissions (emissions rates) from fires based on vegetation type. The characteristics of various vegetation types provide information regarding the nature of fuel burned, the expected fuel load, and the types and amounts of aerosol emitted in a burn event (Mahmud, 2000; Andreae and Merlet, 2001). Lobert et al. (1999) summarizes an inventory conducted of total annual biomass burned, and Streets et al. (2003) compiled available data on biomass burning emission rates for Southeast Asia. Ichoku and Kaufman (2005) discuss the ability to derive emissions coefficients directly from satellite data, and note that their current algorithm can estimate these coefficients with about 50% accuracy. Continued research in this area will likely greatly contribute to the utility of remote sensing-based products to estimate biomass burning.

5.2 Illustration of fire-aerosol correspondence

Figure 1 (panels a and b) present a map of mainland Southeast Asia with the spatial distribution of aerosols and fires/thermal anomalies for two days during the dry season, 2004: 30 January and 25 March. On 30 January, there were 1,335 fire pixels. These pixels do not necessarily correspond only to highland areas, but are also found in coastal plains (likely due to the burning of agricultural residue). The distribution of aerosols was fairly spatially coincident with the fires, and the highest concentration of aerosols was centered around the largest collection of fires. 25 March was the day with the most detected fires in 2004 (a total of 4,482 fire pixels), and these fires are most concentrated in upland areas. Aerosol optical depth (AOD) was high in much of the subcontinent that day (a range of 0-4.319), and there was some spatial correspondence between fires and AOD in the northwestern and north-central portions of these countries. Large parts of Laos, Cambodia and Vietnam, where many fires occurred, did not have correspondingly high levels of AOD.

5.3 Simulation-based approaches

Besides satellite and ground based observations, numerical simulators are another type of tool that has been used to study aerosol transportation and its interaction with other atmospheric gases. Given the sparseness in spatial and temporal coverage of satellite measurements and the transportation of aerosols, it is hard to obtain stable and accurate characterization of the contribution of fires and the spatial-temporal structure and transportation pattern of aerosols solely based on these observations. However, global chemical transport models have full coverage in the spatial and temporal domain. Therefore, a combination of satellite/ground based observations and numerical simulators may provide better information.

Along this research direction, observations from the Measurements of Pollution in the Troposphere (MOPPIT) instrument onboard the EOS Terra satellite, and the simulation results from the Model for OZone And Related chemical Tracers (MOZART) have been used to study the transportation of CO generated from wildfires in Alaska and Canada in summer 2004 (Pfister et al., 2005). Aerosol optical depths observations from MODIS and AERONET have been combined with a global 3-D chemical transport model (GEOS-Chem) to quantify Asian aerosol enhancements in U.S. surface air in 2001 (Heald et al., 2006). The Georgia Tech/Goddard Global Ozone Chemistry Aerosol Radiation and Transport (GOCART) model can also simulate major aerosol components using assimilated data.

5.4 Data alignment issues

Analysis of data from various sources is a frequent challenge for researchers who analyze dynamic physical systems, especially due to the differences in spatial and temporal resolution and coverage. For example, the MISR Level-2 aerosol product has a spatial resolution of 17.6 km by 17.6 km, while both the MODIS Fire and Thermal Anomalies and land cover products have a spatial resolution of 1 km by 1 km. When they are aligned to a common grid, the distortion needs to be well studied. For temporal resolution and coverage, MISR has a much longer repeating cycle (about 9 days at the equator) than MODIS (almost daily at the equator), because MISR has a narrower swath (360 km) compared to the MODIS swath (2330 km). On top of the resolution and coverage difference, missing data (or non-retrievals) also pose great difficulties for data analysis and need to be handled carefully. For example, MISR does not retrieve aerosol information if the region is covered by cloud. These missing values should be treated differently than those non-retrieved pixels on which the aerosol retrieval algorithms fail.

6. Summary

It has long been recognized that human activities have implications for the global system. Land-atmosphere interactions are one class of a set of important coupled human-environment processes, and the specific relationships between biomass burning and carbonaceous aerosol emissions are relatively poorly understood, particularly in Southeast Asia (Woo et al., 2003), compared to sub-Saharan Africa or South America, where biomass burning dominates all other aerosol sources (Chin et al., 2002). Because carbonaceous aerosols have adverse effects on the radiation balance and air pollution, better knowledge regarding the extent and pattern of land-use practices resulting in burning as sources of aerosol distributions would be of use to scientists and policy makers. Due to the spatial and temporal variability of atmospheric transport patterns, local land-use/cover change can result in unpredictable changes in regional aerosol distributions. The association between biomass burning and aerosols determines the impact of local land-use/cover change events on regional aerosol concentrations.

Land-use systems in Southeast Asia are undergoing profound transformations, as upland shifting cultivation is increasingly replaced by market-oriented crop production. There are two relevant temporal trends reflected in land cover and fire practices. First, there are shifts in land-use systems relating to policy changes, such as new land rights in the postsocialist economies of Vietnam and Laos. Secondly, there are important seasonal variations in the vegetation burned relating to agricultural production practices. In addition, background levels of carbonaceous aerosols are increasing over time due to industrial pollution and other combustion of fossil fuels. In particular parts of the region, such as Vietnam, these changes have been staggering. Increasing market linkages between this region and consumers in the rest of the world have implications for the use of fire, for land clearing and the burning of crop residue. Deforestation trends show that market linkages can in certain circumstances promote the conservation of forests and natural landscapes, but in other settings, lead to greater land clearing. In any case, any policy designed to address biomass burning must acknowledge the critical supports of market-oriented land-use systems (e.g., physical infrastructure, financial support and technology), and thus many factors must be considered in order to forecast likely scenarios for future biomass burning. Policy in the region will have to consider the spatial and temporal distribution of agricultural residue burning, and large-scale clearings for commercial agriculture.

The purpose of this review was to highlight how an integrated understanding of land-atmosphere interactions in mainland Southeast Asia, where the concern about air pollution has been dramatically increasing during the last several decades, is essential. It is known that biomass burning, as well as other anthropogenic factors, are the main culprits behind the observed increase in air pollution (Uno et al., 2003), but uncertainty remains in the ability to match the sources of these aerosols to the regional concentrations of carbon and the implications for the energy balance (Andreae and Crutzen, 1997).

The broader international research community has noted that fire mapping and monitoring by satellite is a crucial component of a broader effort to understand global change. However, simple mapping of fires is not enough to estimate the overall atmospheric effect of the biomass burning (Mota et al., 2005). Effectively linking fire events and regional atmospheric carbon particles over space and time will provide additional insight into the ultimate effects of land-use/cover change events on climate and the earth's radiation balance.

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Table 1. Recent trends in forest cover in mainland Southeast Asia

Country	Land Area, 1 000 ha.	Forested Area					Burnt Area, 2000 (1 000 ha)	
		1990	2000	2005	% Change 1990-2000	% Change 2000-05	Area	% Area
Burma	65,755	39,219	34,554	32,222	-11.89	-6.75	383	2.17
Cambodia	17,652	12,946	11,541	10,447	-10.85	-9.48	147	0.64
Laos	23,080	17,314	16,532	16,142	-4.52	-2.36	1,106	1.68
Thailand	51,089	15,965	14,814	14,520	-7.21	-1.98	197	0.39
Vietnam	32,549	9,363	11,725	12,931	25.23	10.29	39	0.12

Source: FAO, 2007b; Brown and Durst, 2003

Table 2. Recent trends in selected crop production in mainland Southeast Asia.

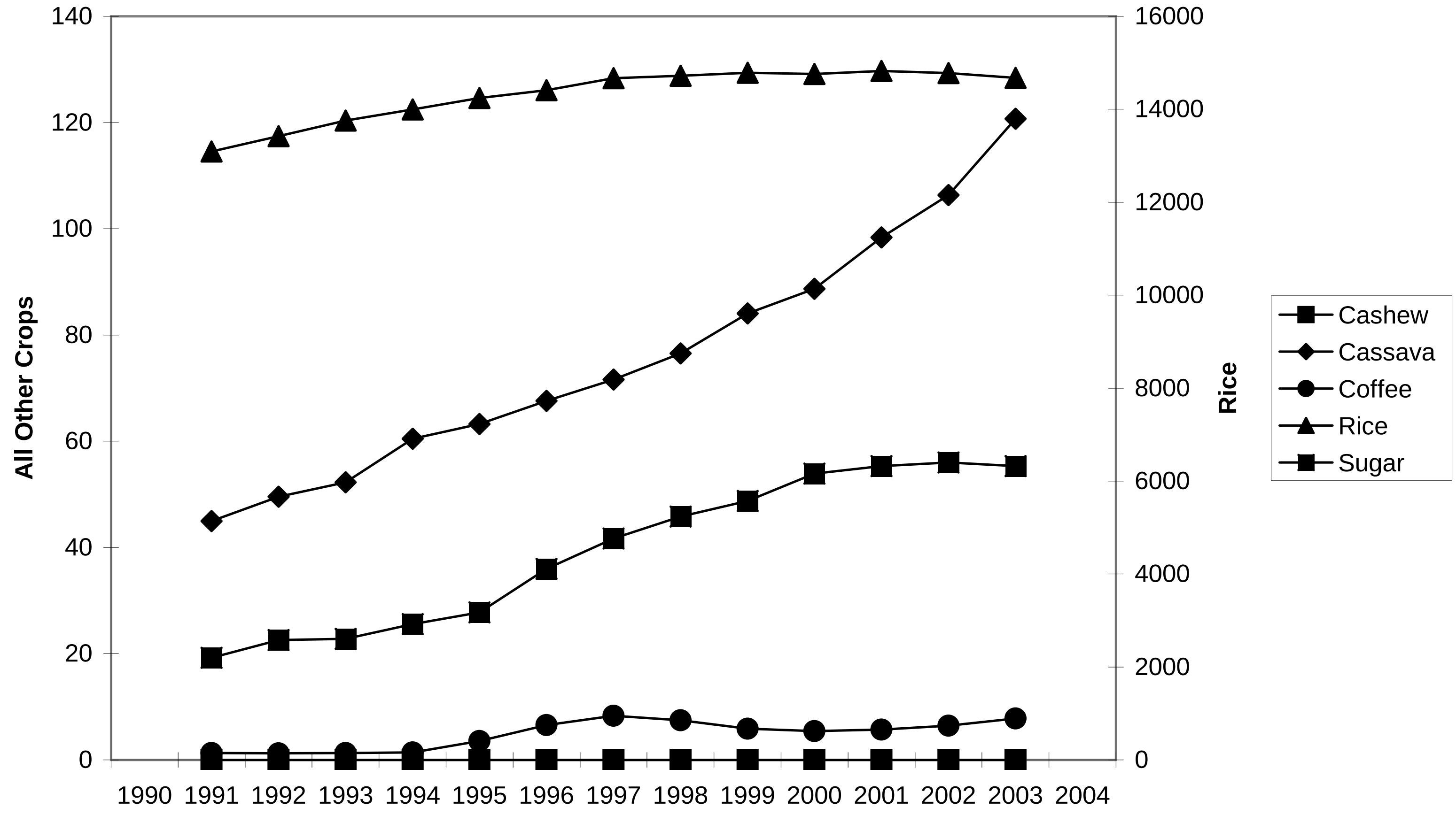
	Burma			Cambodia			Laos			Thailand			Viet Nam		
Crop output, 1,000 tons	1990	2004	% Total output 2004	1990	2004	% Total output 2004	1990	2004	% Total output 2004	1990	2004	% Total output 2004	1990	2004	% Total output 2004
Cashew nuts	0.00	0.00	0.00	0.00	0.41	0.01	0.00	0.00	0.00	11.85	24.00	0.02	140.00	825.70	1.03
Cassava	52.64	139.00	0.32	60.00	362.05	5.99	65.00	55.50	1.30	20,700	21,440	15.89	2,275	5,572.80	6.96
Coffee, green	1.38	3.01	0.01	0.16	0.31	0.01	5.30	23.10	0.54	71.48	61.77	0.05	92.00	834.60	1.04
Rice, paddy	13,971	23,700	54.83	2,500	4,170	69.05	1,507	2,529	59.32	17,193	23,860	17.68	19,225	35,887	44.82
Sugar Cane	2,198	6,678	15.45	258.00	130.36	2.16	111.90	223.30	5.24	33,561	64,973	48.15	5,405	15,879	19.83
% Change in Production	1990-2000	2000-2004		1990-2000	2000-2004		1990-2000	2000-2004		1990-2000	2000-2004		1990-2000	2000-2004	
Cashew nuts	na	na		na	na		na	na		85.65	9.09		93.14	205.36	
Cassava	46.75	79.94		146.27	145.03		9.23	-21.83		-7.91	12.47		-12.72	180.56	
Coffee, green	31.16	66.30		87.50	3.33		343.40	-1.70		12.74	-23.35		772.28	4.00	
Rice, paddy	52.62	11.14		61.04	3.58		46.06	14.86		50.32	-7.68		69.20	10.32	
Sugar Cane	168.14	13.30		-36.36	-20.60		165.38	-24.80		57.36	23.03		178.31	5.55	

Source: FAO, 2007a

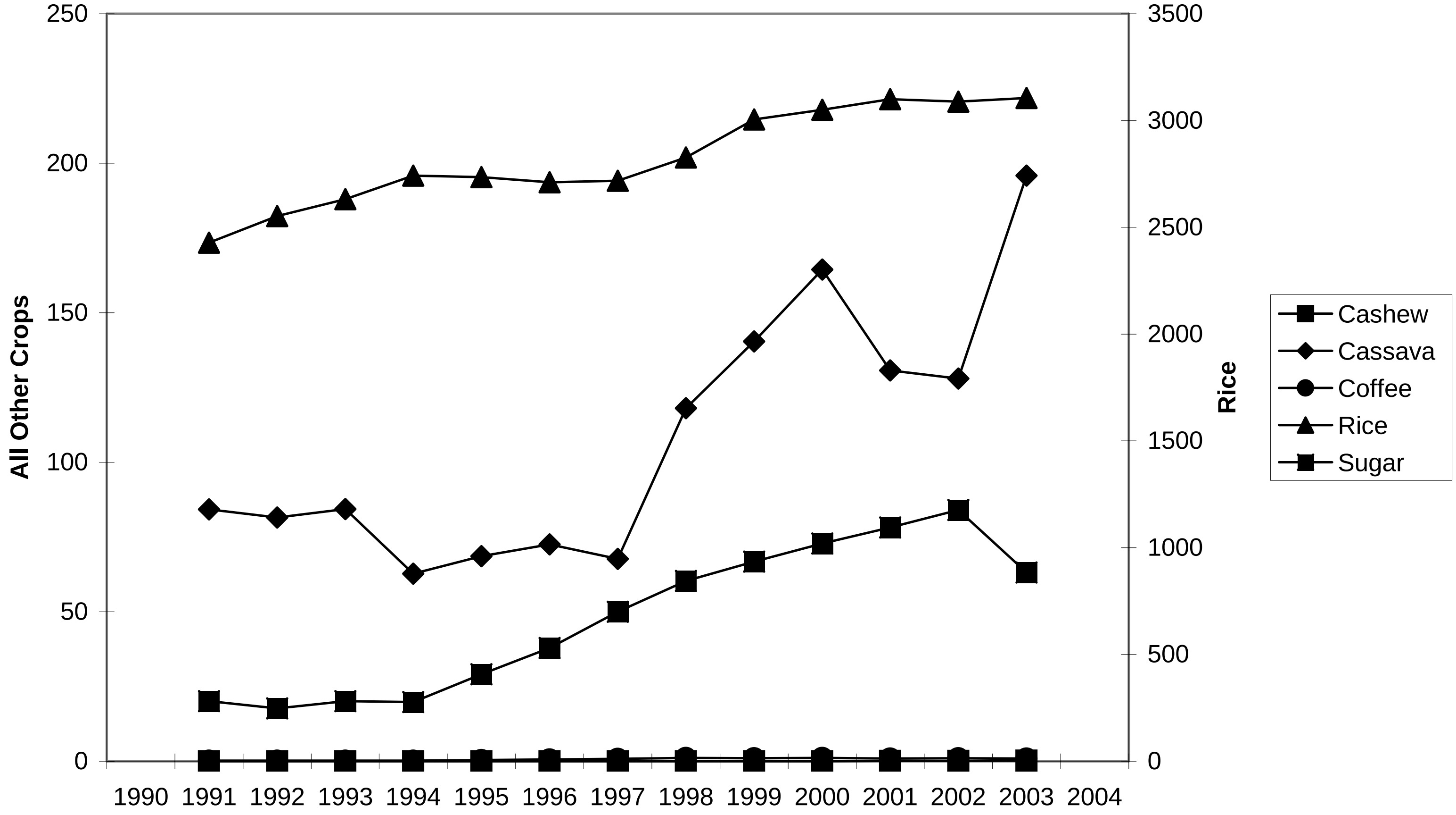
Table 3. Data sources for studying biomass-burning/aerosol relationships

Type	Name	Source	Description	Spatial resolution	Temporal coverage	Notes / References
Fire	Advanced Very High Resolution Radiometer (AVHRR) Fire Identification, Mapping and Monitoring	National Oceanic Atmospheric Administration Satellite Information System	Nighttime fire detection	1.1 km	1995 – present; daily coverage	FIMMA has been folded into the Hazard Mapping Product
	European Space Agency World Fire Atlas	Along-Track Scanning Radiometer, European Remote Sensing Satellite	Nighttime detection; two algorithms with different temperature thresholds	1km	1995-present	Arino et al. , 2005
	Hazard Mapping System Fire and Smoke Product	Created from a combination of GOES, AVHRR, MODIS and Defense Meteorological Satellite Program/Operational Linescan System (DMSP/OLS) data	Locations of fires and smoke plumes	0.5 degree	1994-present; Daily fire position tables;10-day synthesis	Eidenshink and Faudeen, 1994
	Moderate Resolution Imaging Spectroradiometer (MODIS, Aqua and Terra) Thermal Anomalies/Fire Daily L3 Global 1km SIN Grid	MODIS (MOD14A; MYD41A) Level 3; EOS Gateway	9 categories of missing, water, cloud, non-fire, unknown, and low-nominal-high confidence fire	1 km	2000-present daily; data compiled in eight-day product	Giglio et al., 2006
Aerosols	AERONET (AEROSOL ROBOTIC NETWORK)	A federation of ground-based aerosol radiometers	Spectral aerosol optical depth (AOD), inversion products, and precipitable water	In situ; 180 monitors worldwide	Varies locally	Holben, et al., 1998
	Envisat's Medium Resolution Imaging Spectrometer (MERIS)	European Space Agency (ESA)	Aerosol optical thickness and the Angstrom coefficient	1040 x 1200 m	2003-present; Global coverage every 3 days	Rast and Bezy, 1999
	MISR Level 2 Aerosol/Surface Data	MISR (MIL2ASAE) Level 2	Spectral Optical Depth; Particle size and shape, Angstrom exponent	17.6 km	2000-present; 9 days at the equator, 2 days at poles	Diner et al., 1998
	MODIS Level 2 Aerosol Product	MODIS(MOD04 and MYD04)	Optical Depth and aerosol size distribution (oceans)	10km	2000-present daily;	Kaufman et al., 1997
	POLarization and Directionality of the Earth's Reflectances (POLDER)	Centre National D'Etudes Spatiales (CNES) France	Land and Ocean products; Aerosol optical thickness, Angstrom exponent,	1080mx1260 m	1996-present	Deschamps et al., 1994
Emissions inventories	(Global coverage; often calibrated from field campigns) Andreae and Merlet 2001; Lobert et al. 1999 ; Mahmud 2000; Streets et al. 2003					

Figure 1 (a-e). Trends in Major Crop Production, 1990-2004 (Source: FAO, 2007a).
1 a) Burma



1 b) Cambodia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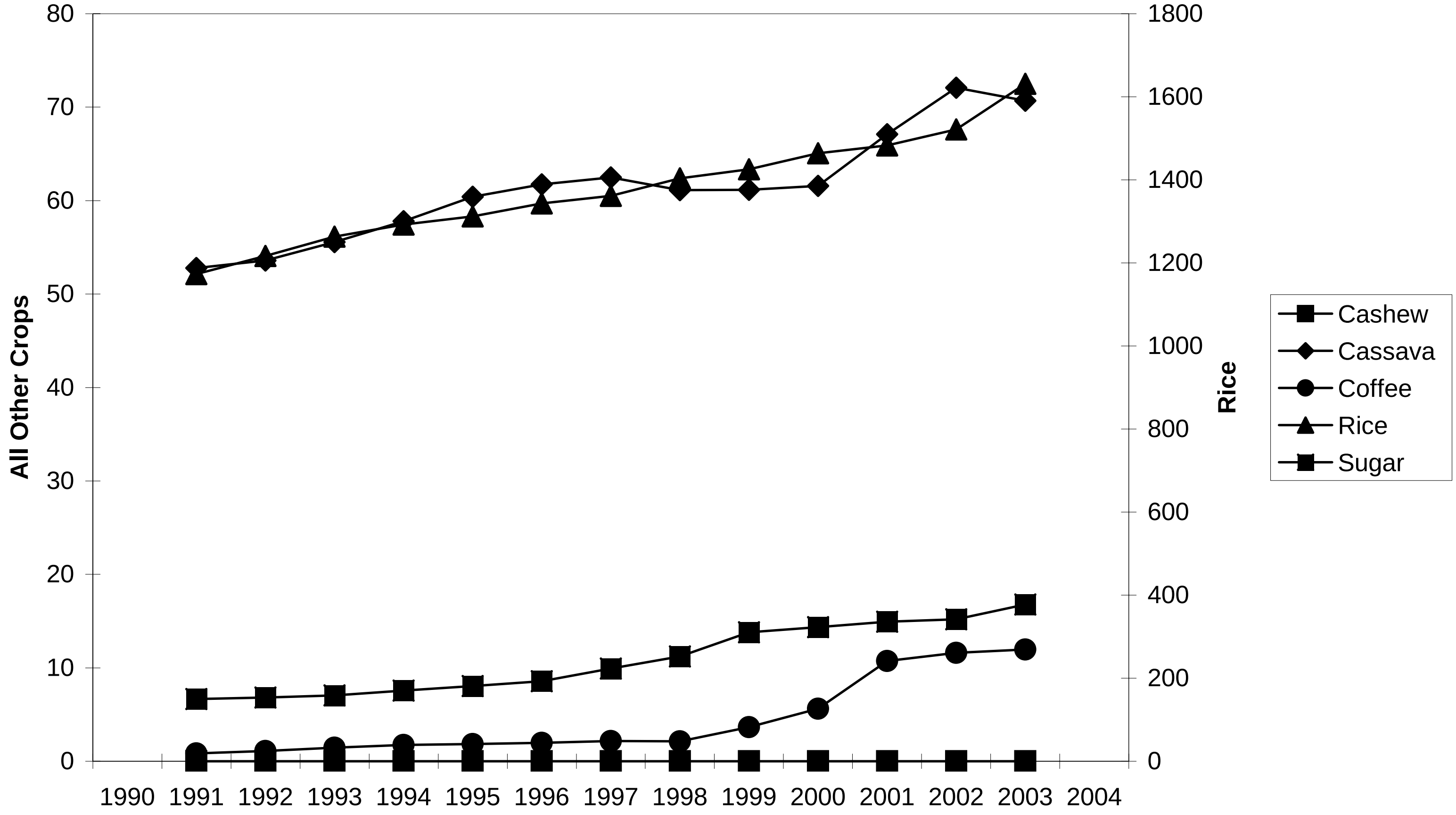
200
150
100
50
0
All Other Crops
3500
3000
2500
2000
1500
1000
500
0
Rice
1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004
Cashew
Cassava
Coffee
Rice
Sugar

1 c) Laos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60
50
40
30
20
10
0
All Other Crops
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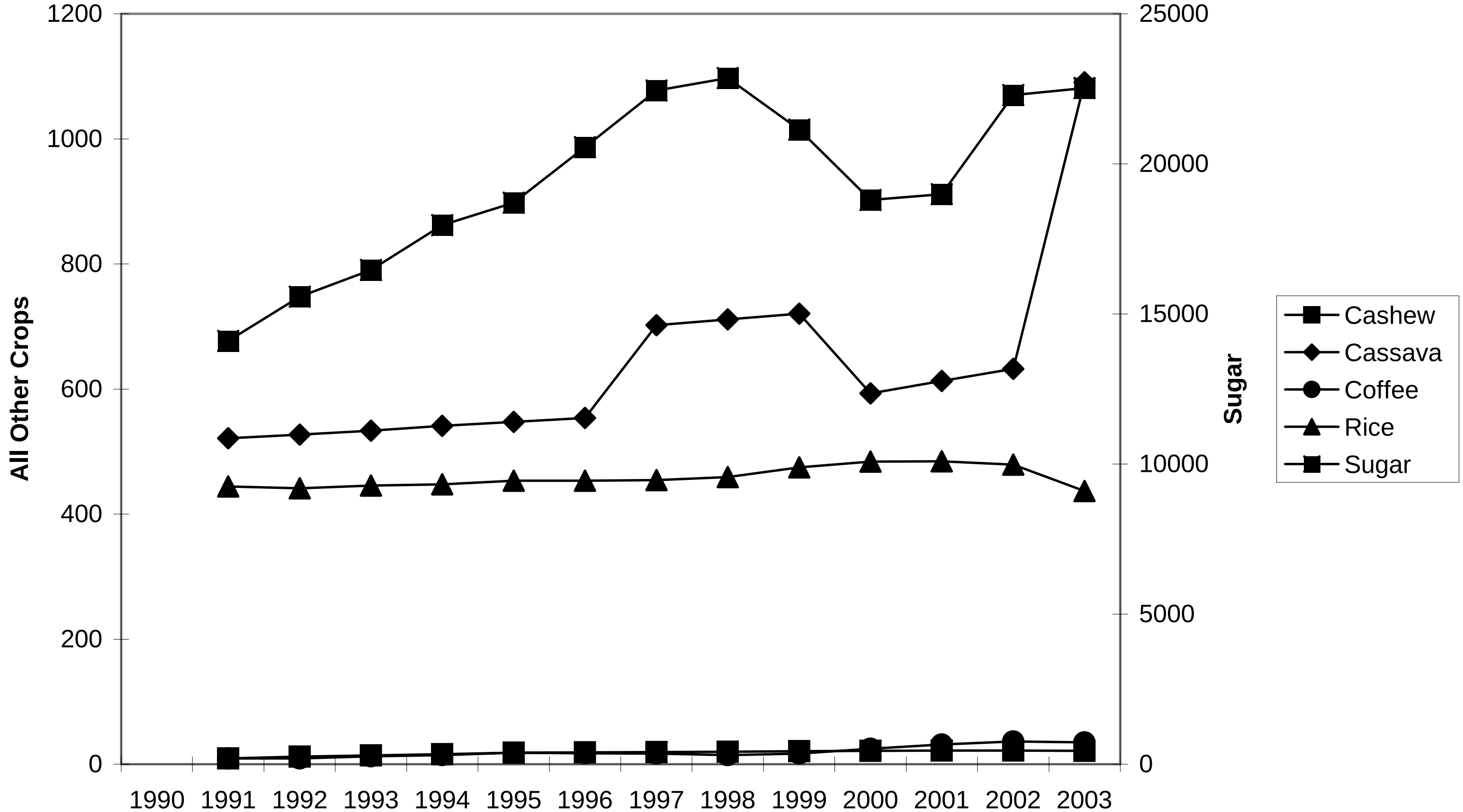
1600
1400
1200
1000
800
600
400
200
0
Rice
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
Cashew
Cassava
Coffee
Rice
Sugar

1 d) Thailand


All Other Crops
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600
800
1000
1200
Sugar
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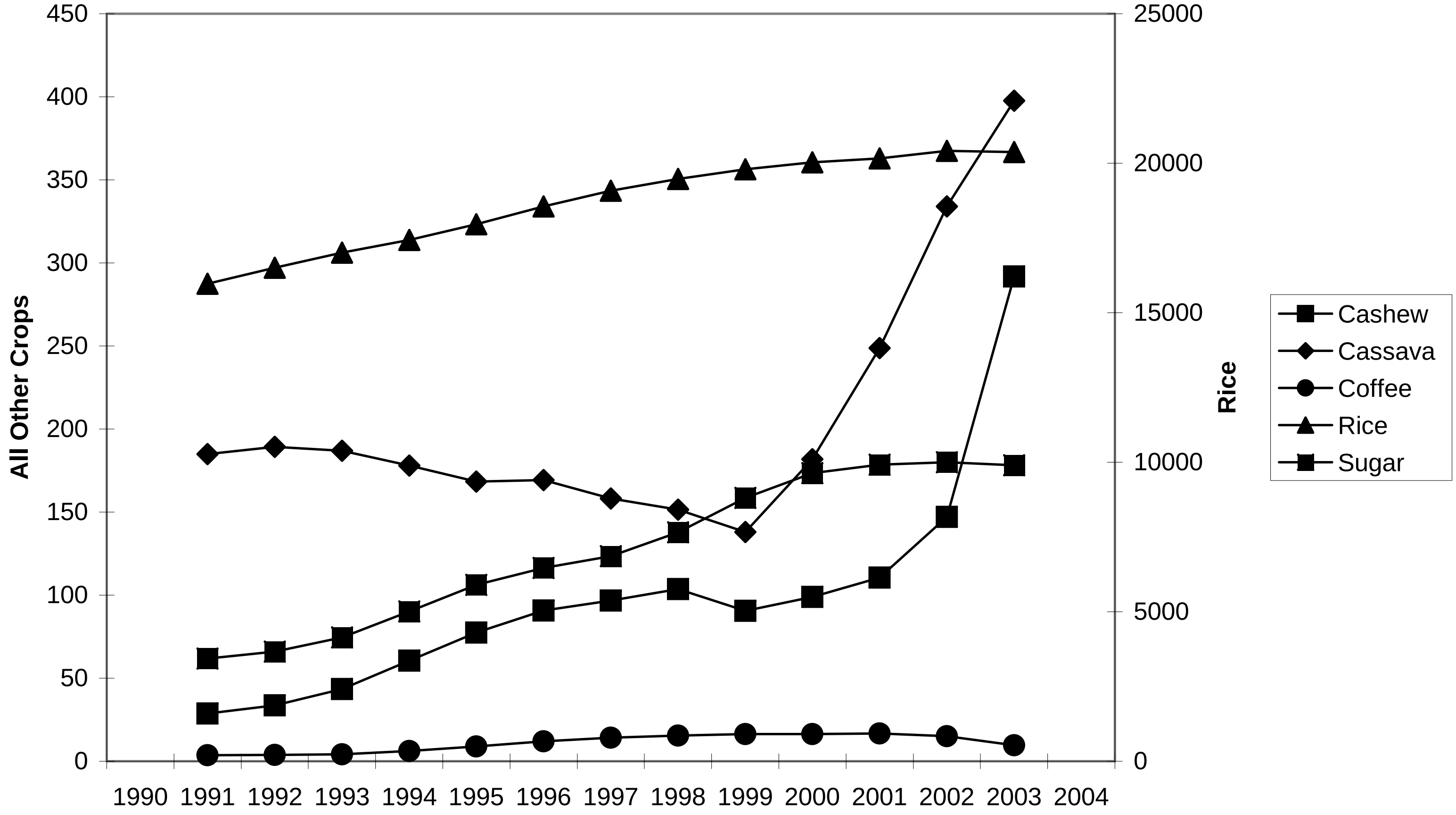
5000
10000
15000
20000
25000
1990
1991
1992
1993
1994
1995
1996
1997
1998
1999
2000
2001
2002
2003
Cashew
Cassava
Coffee
Rice
Sugar

1 e) Vietnam



All Other Crops
Rice
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400
350
300
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100
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0
25000
20000
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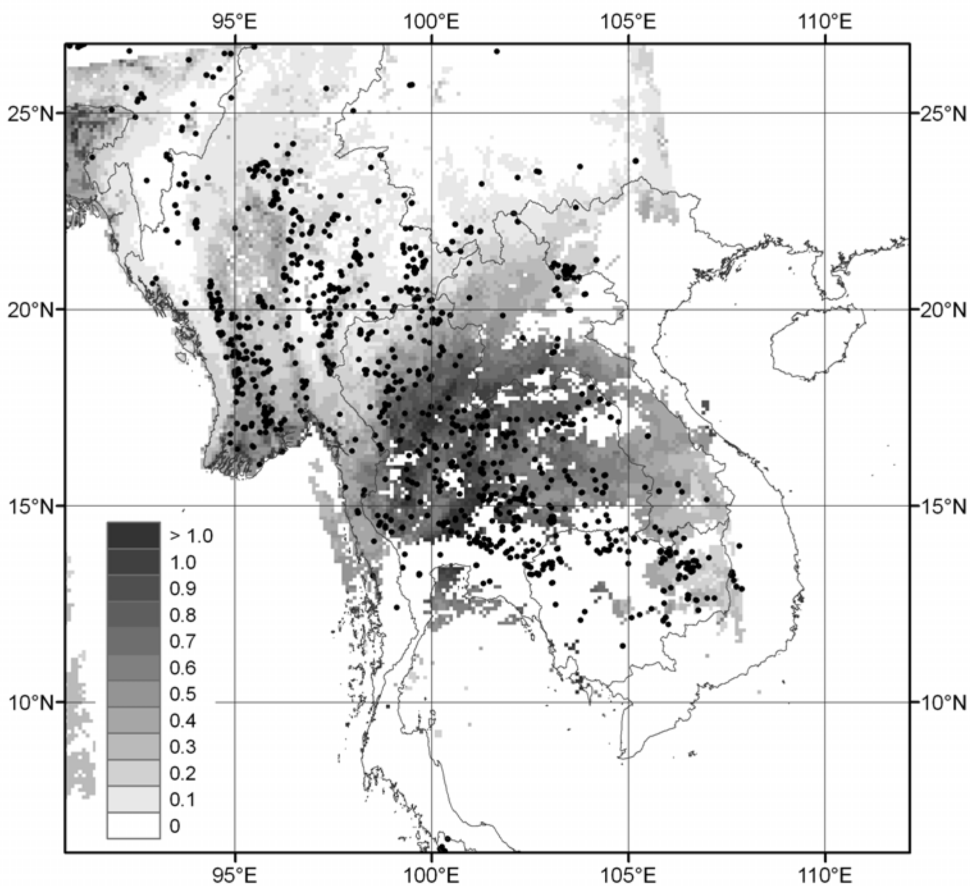
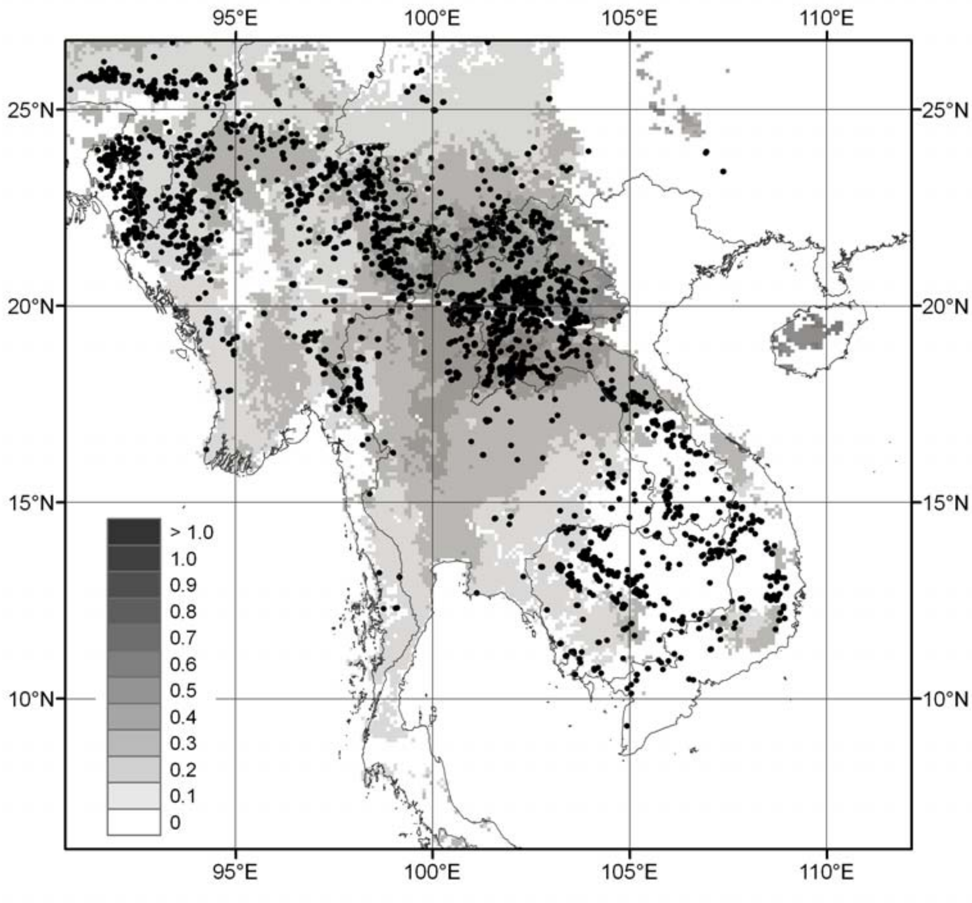
10000
5000
0
1990 1991 1992 1993 1994 1995 1996 1997 1998 1999 2000 2001 2002 2003 2004
Cashew
Cassava
Coffee
Rice
Sugar

Figure 2 (a-b). The spatial distribution of fires and thermal anomalies, and aerosol optical depth on 30 January 2004 and 25 March 2004 (Source: Level 3 Fire products for MOD14A (Terra) and MYD41A (Aqua); and MODIS Level 2 Aerosol Optical Thickness [MOD04_L2 and MYD04_L2).

2 a)



2 b)



95°E
100°E
105°E
110°E
25°N
20°N
15°N
10°N
> 1.0
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0