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*Chapter 6*

# POTENTIAL FOR ADVANCING FIRE RESEARCH IN AMAZONIA BY INTEGRATING GROUND-BASED, REMOTE-SENSING AND MODELING STUDIES FOR THE REGION

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## ABSTRACT

Fire research is key for understanding the ecosystem functions of Amazonia and the sustainability of land-use practices in the region. Fires are significant disturbances to biogeochemical cycles, and have important links to land use and climate. Major methods for studying fires include fieldwork, remote sensing and modeling. The potential benefits from the synergy of these methods are numerous. Occasional ground-based fire activity information can be supplemented by frequent data from satellites. Remote-sensing fire products can be improved using accuracy assessments based on ground observations. Models rely on calibrations and validations using both ground- and satellite-based data, and are the only tools for projecting future fire activity and effects. The review of several studies representing fire research methods with emphasis in their synergy show that different methods typically provide information at different spatial and temporal scales, and there is an important tradeoff between datasets resolution and domain. Ground-based methods can provide information at high spatial and temporal resolution, but they do not usually provide data for large domains. Remote sensing and modeling studies can provide information for larger domains, but their data are usually at lower resolution, which complicate their interpretation for studying fires. Studies based on the synergy of all methods have a great potential to significantly advance fire research. One important outcome expected from this type of studies is the possibility of building a class of models that can be used for multi-scale applications, ranging from warning systems to climate and Earth System modeling. While combinations of multiple methods are desirable, important challenges exist including technological, expertise and resource needs. The perspectives for overcoming these challenges are promising because the recent advancements in technology and increases in multidisciplinary expertise, but will depend on sustained or increased budgets for supporting relevant research.

## 1. INTRODUCTION

The importance of fires as a strong disturbance in ecosystems in Amazonia has motivated the implementation of several studies to assess their occurrence, behavior and effects (e.g. Andreae et al. 1988, Fearnside et al. 2001, Carvalho et al. 2001, Cochrane 2003, Cardoso et al. 2003). The results and conclusions from many studies have been reviewed in previous publications. For example, Nepstad et al. (1999) is one of the most comprehensive reviews on occurrence, ecological impacts and economical effects of fires in Amazonia, including an assessment of relations between fire type, burned area and property size in five locations along the Arc of Deforestation in 1995. Conclusions from Nepstad et al. (1999) focus on alternatives to reduce the environmental and economical problems caused by accidental fires escaping from managed lands. In particular, those authors emphasize that the expansion of the agricultural frontier should be reduced, the agricultural production should be intensified in areas already settled, and the legislation should be updated to encourage the prevention of accidental fires.

In addition to the effects of fires on tree mortality and forest structure, Barlow and Peres (2004) reviewed the impacts of forest fires on vertebrates. Reviews of the impacts of fires on animals in Amazonia are not common. Barlow and Peres (2004) recapitulate that at the short term, most of terrestrial animals with reduced mobility are wounded or killed, and even arboreal species are affected by smoke; rapid-moving species also have problems as they will potentially have to compete for resources outside their original habitats. Barlow and Peres (2004) also conclude that remaining individuals can be easily hunted and suffer from food shortage and the need for switching diet, and that long-term effects on animals are equally significant and only few groups such as large browsers, small cats and reptiles were reported to recover well from fires.

Cochrane (2003) reviewed the occurrence and impacts of fires as a consequence of development and deforestation in tropical forests. Cochrane's review applies for the whole tropics, but concentrates in Amazonia where he is one the most experienced fire researchers. Cochrane remarks that the use of fire as an efficient tool for land clearing and fertilizing lead to important property and environmental damages, including negative effects on ecosystem structure, human health and atmospheric composition. His major conclusions focus on the need for additional and specific studies for tropical forests. For example, he emphasizes the need for new fire susceptibility and behavior models that can properly account for fuel moisture dynamics in these regions, and the need for studies that collect fire data at the local scale.

Reviews on fires at global scale can also be cited because Amazonia is recognized as a region where fire occurrence and impacts have global implications for biodiversity losses (WCMC 1992), changes of land cover (Crutzen and Andreae 1990) and increases in greenhouse gases in the atmosphere (Andreae and Merlet 2001). Reviews on fires in

Amazonia share at least three points of view. First, fire occurrence has strong environmental effects. Second, the contemporary patterns of fires greatly differ from the expected low burning activity inferred from long-term records of fire activity across the basin. Third, the increased fire activity is the result of human activities.

This review builds on previous reviews by taking a different perspective. It reviews methods for fire research in Amazonia with emphasis in their synergy, and provides a synthesis that accounts for a significant number of cases representing typical applications of the fire research methods. In the case of fire research, they can be classified into the broad categories of ground-, remote sensing- and modeling-based methods. Ground-based methods use direct measurements to assess fires occurrence, behavior and effects. Remote sensing-based methods use airborne observations and sensors. Modeling studies search for mathematical relations that can numerically reproduce fires dynamics and effects.

The central thesis in this chapter is that significant progress in fire research can be achieved from studies where multiple methods interact (Figure 1.1). For example, occasional ground-based fire activity information can be supplemented by frequent data from satellites. Remote-sensing fire products can be improved by accuracy assessments based on ground observations. Modeling studies rely on calibrations and validations using both ground- and satellite-based data. Models can be used to estimate fire activity, behavior and consequences in cases where ground or satellite observations could not be made, and are the only tools for projecting future activity

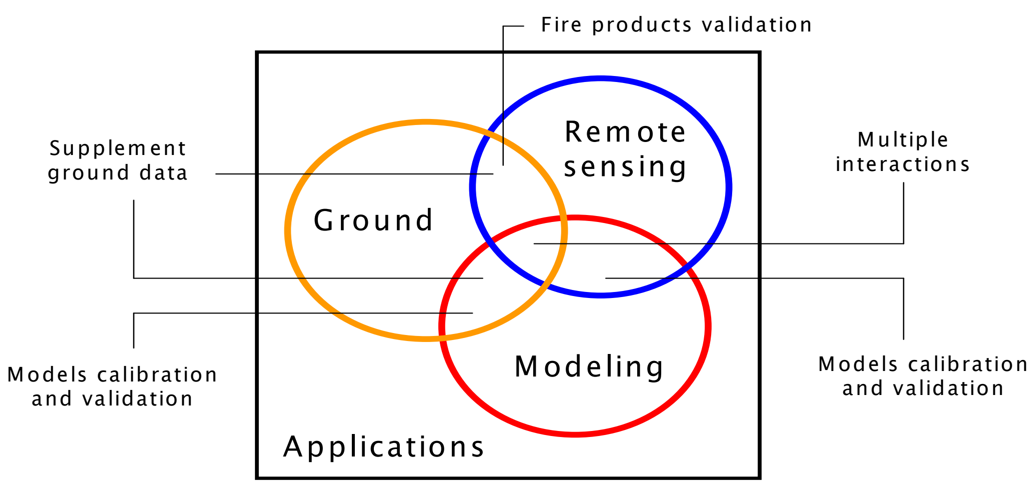


Figure 1. Benefits from interactions between methods for fire research. Occasional ground-based fire activity information can be supplemented from frequent data from satellites. Remote-sensing fire products benefit from accuracy assessments based on ground observations. Modeling studies rely on calibrations and validations from both ground- and satellite-based studies. The synthesis power built into models allows for diagnostic and prognostic studies. Models can be used to estimate fire activity, behavior and consequences in cases where ground or satellite observations could not be made, and are key for projecting fire activity in response to future scenarios of land cover, land use and climate.

# 2. Fire Research Methods

Below, several studies are reviewed representing different methods for providing information on fires in Amazonia (Table 1.1). The purpose of these studies as well as the results they provide can be broadly organized into three main categories of fires occurrence, behavior and effects. Information on fire occurrence or activity is based on fire position and time. Data on fires behavior are reported as the physical properties of fires such as flame length, depth, rate of spread and heat flux. Most of the data on fire effects are provided as land and atmospheric changes caused by fires. Data on fire effects typically include biomass consumed, area burned, changes in land-surface albedo, vegetation mortality, and changes in carbon and nutrient pools. The impacts on atmospheric composition are usually measured as fluxes of gases and aerosols emitted by fires.

## 2.1 Ground-Based Methods

Ground-based studies are based on local fire observations. For example, patterns of yearly fire occurrence were studied in detail by Nepstad et al. (1999) based on interviews to landholders at 202 properties in 5 different regions along the Arc of Deforestation in Amazonia. In that survey, landholders reported that 77600 hectares burned inside their rural properties in 1994. From the total area estimated, 13% burned as deforestation fires, 20% as forest surface fires, and 67% as fires on land already deforested (Nepstad et al. 1999). The burned fraction of the properties decreased with property size: small (<100 ha), medium (101-1000 ha), large (1001-5000 ha), and very large (>5000 ha) properties had ~23%, ~19%, ~16%, and ~5% of their areas burned, respectively. On the other hand, the extent of the area burned increased with property size: in average <50 ha, 100 ha, 300 ha, and 1800 ha, burned in each small, medium, large, and very large property, respectively.

Estimates of fire occurrence on longer time scales have been made using sediment analyses, such as in Turcq et al. (1998) and Sanford et al. (1985). Turcq et al. estimated fire occurrence from lake sediments in Eastern Amazonia, and showed that natural fires have influenced forests for the last 7000 yrs, potentially affecting current patterns of forest structure. Sanford et al. analyzed charcoal in the soils of north central Amazonia, and showed that fires have been disturbed lowland forests in the region for the past 6000 years.

Ground-based studies are essential to provide detailed information on fire effects. For example, Kauffman et al. (1998) estimated that fires in pastures consumed in average 21-84% of the total aboveground biomass, reduced 19%-81% of the aboveground pool of carbon and emitted $11\text{-}21 \cdot 10^3$ kg C/ha. Hughes et al. (2000) studied fires in regenerating forests, where fires consumed in average 52-58% of the aboveground biomass, reduced 56% of the aboveground carbon pool and emitted $20\text{-}47 \cdot 10^3$ kg C/ha to the atmosphere. Fearnside et al. (2001) estimated that the burning efficiency in primary forests located close to Manaus was equal to 28.3%. In the same region, Carvalho et al. (2001) estimated that overall biomass gasification efficiency during fires is equal to 25.1% and leads to the emission of $51 \cdot 10^3$ kg C/ha. Measurements by Dias et al. (1996) showed that in average fires caused surface albedo in savannas to reduce from 0.15 to 0.05. Miranda et al. (1996) showed that fires in woody savannas consumed 94% of the vegetation and reduced the surface albedo from 0.11 to 0.03.

Some ground-based studies combine information on fires occurrence and effects. For example, Guild et al. (1998) studied land-use fires in Rondônia showing that fires are commonly involved in land use as an effective and inexpensive tool for converting forest areas into croplands and pastures, and to keep the forest vegetation from re-growing. Based on that study, pasture fires consumed 31% of the aboveground biomass and lead to mean nutrient losses of $14 \cdot 10^3$ kg C/ha, 199 kg N/ha and 16 kg S/ha. In slashed primary forests, the mean combustion factors was 48% and total nutrient losses were $79\text{-}102 \cdot 10^3$ kg C/ha, 1019-1196 kg N/ha and 87-96 kg S/ha (Guild et al. 1998).

Cochrane and Schulze (1999) studied relations between fires and dry conditions, and the effects of fires on the structure and species composition in forests in eastern Amazonia. In that study, they show that fires can kill saplings and seedlings reducing or even preventing trees to reach the reproductive age in the forest. In those forests, fires were generally associated with severe dry conditions, and fire susceptibility increased with previous burning activity. Uhl and Kauffman (1990) also studied fires in eastern Amazonia, showing that typically trees in tropical forests are not adapted to fires. According to that study, primary forests take longer to become flammable during rainless periods than logged forests and pastures. Whereas primary forests were flammable after ~one rainless month, logged forests and cattle pastures become flammable after ~one week and ~day of dry conditions, respectively.

One of the few studies providing combined information on fire occurrence, behavior and effects in Amazonia was performed by Cochrane et al. (1999) in Pará. In that study, the authors show that accidental fires escaping from pastures and other managed areas are major threats to forests in the region. They also provide detailed information on fire behavior and characteristics, including information on flame height, depth, rate of spread, residence time, intensity and heigth of crown schorch. A major conclusion from Cochrane et al. (1999) is that recurrent forest fires significantly increase fire susceptibilty, fuel load and fire severity potentially leading to positive feedbacks in fire activity.

Ground-based studies are also critical to collect data for assessing the accuracy of satellite-based fire data. For example, as part of the Smoke Clouds and Radiation-Brazil (SCAR-B) experiment, Prins et al. (1998) performed three prescribed burns in Rondonia, Brazil, to assess the Geostationary Operational Environmental Satellite 8 (GOES-8) Automated Biomass Burning Algorithm (ABBA) fire product. In those experiments, one fire could not be detected due to cloud cover and the remaining two fires were detected and had their size and temperature estimated. The ABBA product, however, overestimated fire size. Controlled burns set for emission studies during the field experiments BASE-A (Kaufman et al. 1992) and BASE-B (Ward et al. 1992) were also used to assess fire data from the Advanced Very High Resolution Radiometer (AVHRR) sensor onboard NOAA polar orbiting satellites. One fire, set on September 1989 in Mato Grosso was detected from satellites NOAA-10 and NOAA-11. The other controlled fire, set on September of 1990 in Pará, was detected from NOAA-9 and NOAA-11 (Setzer et al. 1994).

A new class of ground-based analyses for assessing satellite fire data is presented in Cardoso et al. (2005). That method consists of the collection of passive ground-based information on both fire and non-fire occurrence, which are statistically related to data from corresponding satellite fire products. Using ground data collected in two regions in Amazonia in 2001 and 2002, Cardoso et al. found that the total accuracy for AVHRR- and MODIS-based (MODerate Resolution Imaging Spectroradiometer) fire products was very high and dominated by accurate non-fire detection, and that fire-detection accuracy was much lower and errors of omission were much larger than errors of commission for both datasets.

## 2.2 Remote Sensing Based Methods

Due to broad spatial and temporal coverage, satellite-based fire products have the potential to provide major datasets on fire activity and area burned for large regions and long periods. Several examples of satellite-based systems in use to monitor fires in Amazonia are reviewed. They include active-fire products represented by the CPTEC-INPE fire monitoring system (CPTEC 2008a, Setzer and Malingreau 1996), the Automated Biomass Burning Algorithm (ABBA) (UW-CIMMS 2008, Prins et al. 1998), the MODIS fire products (Justice et al. 2002), and fire detection using TRMM (Giglio et al 2003). In these products, fire activity data are reported as fire pixels, which are satellite picture elements where active burning is detected. Area burned is provided as part of the global area burned inventories for 2000 from GBA2000 (Grégoire et al. 2002) and GLOBSCAR (Kempeneers et al. 2002). Here, the observations made onboard airplanes and helicopters are also classified as "remote-sensing based". These types of observations are represented here by the work of Kaufman et al. (1992), Ferek et al. (1998), Andreae et al. (1988), and Selhorst and Brown (2003).

The CPTEC-INPE fire product is based on data from the AVHRR sensor onboard NOAA polar orbiting satellites (CPTEC 2008a). In that technique, fire pixels are identified from intensity thresholds in the data collected by the sensor's thermal radiation channel at 4μm wavelength (Setzer and Malingreau, 1996). After detection, some fire pixels are filtered out if there are indications of solar glint on water, soils and clouds. This product detects daily fire activity at spatial resolution ~1km at nadir. Most of the available data are based on detections from nighttime NOAA12 overpasses at 21-23 GMT, and from afternoon NOAA14 overpasses at 16-18 GMT. Data are provided as fire pixels position and time.

The ABBA fire product is based on data from the Geostationary Operational Environmental Satellite 8 (GOES8) (UW-CIMMS 2008). Fires are detected based on information from two thermal channels at 4μm and 11μm wavelength (Prins et al. 1998). Fire pixels are selected if the differences in temperature between the two channels are higher than typical values, and if they are abnormally hotter then surrounding fire-free areas. To avoid false positives, fire pixels are filtered out based on indications that they were confounded with recent burned areas that may be hotter than the background fire-free surface. Because the thermal energy emitted from fires is a function of both area and temperature, data from two channels allow for an additional estimation of fire size (Matson and Dozier 1981). ABBA provides fire pixels position, time, temperature and burning area at ~4 km spatial resolution at nadir. This product has the potential to provide fire information every half hour. Public data are available for fire seasons in 1995 and 1997, detected at 11:45, 14:45, 17:45 and 20:45 GMT.

As part of the NASA's Earth Observing System, active fires are detected using data from MODIS on board TERRA and AQUA platforms (Justice et al. 2002). Fire activity is detected when a pixel has temperature above a certain threshold, and it is significant hotter than the surrounding areas. These temperatures are evaluated using absolute values and differences between thermal data from channels at 4μm and 11μm. The detection criteria change according to the detection time. During the day, the thresholds in absolute and relative temperatures are higher than at night. Pixels classified as water or clouds by other MODIS products are not tested for fire activity. To avoid false positives, fire pixels are filtered out based on specular reflection and daytime thermal reflectance. Data include fire pixels position, time, temperature, burning area, and cloud and water pixels. TERRA overpasses the region at 2:00 and 14:00 GMT, and AQUA at 8:00 and 20:00 GMT. Spatial resolution is 1km at nadir.

In the method by Giglio et al. (2003), active fires can be detected using the Tropical Rainfall Measuring Mission (TRMM) thermal channels at 4 and 11μm, and other channels at 0.63, 1.61 and 12μm. This product evaluates the presence of burning activity in non-water cloud-free pixels. Water surfaces are based on an external dataset, and clouds are identified from reflectance at 0.63, 1.61, and temperature at 12μm. Potential fire pixels are then selected if their reflectance is low, and their temperatures are above a certain threshold, and significantly higher than neighboring fire-free pixels. False positives can be filtered out based on solar reflection conditions. TRMM can provide fire activity data at ~2.2 km spatial resolution within ±38-deg latitude globally. Detection times vary as TRMM local overpass time cycles over 24 hours in nearly a month. Equatorial regions have two observations within ~12 hours every two days. Temperate regions have two or three observations every day. The product described in Giglio et al (2003) provides the following data aggregated monthly at 0.5-deg: number of fire pixels, mean cloud-cover fraction, mean detection confidence and land-cover characteristics.

In addition to data on fire activity, studies were satellites provide estimates of burned area were also reviewed. These products are based on the detection of changes on the land surface from comparisons between repeated images. The GBA2000 (Grégoire et al. 2002) and GLOBSCAR (Kempeneers et al. 2002) are global area burned inventories for the year 2000. GBA2000 is based on images from the VEGETATION instrument onboard the SPOT-4 satellite (Grégoire et al. 2002). GLOBSCAR is based on data from the Along Track Scanning Radiometer (ATSR) onboard the European Remote Sensing satellite (ERS) (Kempeneers et al. 2002).

Several fire studies have been based on observations made onboard airplanes and helicopters. For example, the composition of haze layers originated from fires was investigated by Andreae et al. (1988) using airplane-based air samplings performed over central Amazonia in July and August in 1985. Based on that study, Andreae et al. estimated that 45 Tg of C (emitted as CO) are emitted per year in the South American Tropics due to biomass burning. Emissions from fires were also evaluated from an airplane by Ferek et al. (1998) by measuring the composition of plumes from 19 fires in pastures, savannas and forests during the SCAR-B experiment in 1995. In that study, Ferek et al. found that emission factors in Amazonia were similar to those measured previously in Africa, but particle emissions were 20-40% lower than in boreal forests.

As part of the Fire Monitoring Program at the Brazilian Environmental Protection Agency, several fire observations were made from helicopters over the state of Acre in 2001, and used to evaluate the accuracy of commonly used satellite fire products for Amazonia (Selhorst and Brown 2003). Estimates from those observations suggest that 35% of 2001 fires in Acre were detected with NOAA-12, and 63% were detected with GOES-8 (Selhorst and Brown 2003).

### 2.3 Modeling-Based Methods

Modeling studies search for mathematical equations that can be used to numerically reproduce fire dynamics and effects. These equations are produced based on synchronized datasets of fire dynamics and effects, and their explanatory factors. In Amazonia, combined climate and land-use conditions are believed to be dominant factors for fires in that region. Fire models are very important as synthesis and projecting tools. Model equations quantitatively reflect the knowledge obtained from ground- and satellite-based observations, and allow for evaluating fires where data are rare or non-existent, and projecting fires in response to future scenarios of land cover, land use and climate. Major applications for Amazonia include warning systems for projecting fire risk, and sub-models of fire occurrence and behavior coupled to ecosystem models.

Short-term fire risk is provided by the Brazilian Center for Weather Forecasts and Climate Studies (CPTEC 2008b). This system is in use for preventing and controlling large fires based on short- and medium-range past total precipitation, maximum temperature, minimum relative humidity, and recent fire activity detected using NOAA polar orbiting satellites. Medium-term fire susceptibility was evaluated using the RisQue98 model, produced jointly by the Woods Hole Research Center (WHRC) and the Brazilian Institute for Environmental Research in Amazonia (IPAM) (Nepstad et al. 1999). This model was used to map fire vulnerability for the dry season (July to November) in 1998, based on soil moisture, rainfall, evapotranspiration, timber extraction, forest cover, and fire activity during 1997 detected with the AVHRR sensor.

A small number of fire models have been coupled to ecosystem modeling for Amazonia. Here, two examples were reviewed: the Ecosystem Demography (ED) model (Moorcroft et al. 2001), and the NASA Carnegie-Ames-Stanford Approach (NASA-CASA) model (Potter et al. 2001, van der Werf et al. 2003). In the ED model (Moorcroft et al. 2001) fire occurrence is a function of fuel and climate, and consumes aboveground vegetation and changes soil carbon and nitrogen pools. Fire risk is proportional to local ignition conditions and fuel availability. Fuel is equal to the total above-ground biomass, and ignition is proportional to the length of dry periods. In ED, fires are originated locally but can spread across the grid-cell. The fraction of each gap that is burned is proportional to the total fuel ignited within the grid-cell. The fuel ignited, or the above-ground biomass is totally consumed. There is not direct effect below the ground, but part of the nitrogen and carbon released is transferred to the soil.

The NASA Carnegie-Ames-Stanford Approach (NASA-CASA) model was recently extended to account for fires in tropical ecosystems. In the fire sub-model for NASA-CASA, fire occurrence and behavior are based on remote sensing data, and causing biomass loss and mortality (van der Werf et al. 2003). Fire occurrence is provided by active-fire detections using the TRMM, and is converted into area burned using relations derived from MODIS burned area estimates from locations in Australia, Africa and USA (van der Werf et al. 2003). The fraction of burned area in a grid cell is used to calculate the aboveground live biomass and litter losses and mortality. The values of combustion factors for woody leaves and stems are 90% and 20%, respectively. Combustion factors for herbaceous leaves, coarse litter and fine litter are 90%, 40% and 95%, respectively. Herbaceous leaves and litter have 100% mortality rate. For woody leaves and stems, the mortality factor is proportional to tree coverage and is higher for grid cells with high tree coverage, and low otherwise. The assumption used is that fires in open grasslands generally do not generate enough heat to kill individual trees.

Other fire models have also been built for evaluating risk of fires. For example, a model for the probability of understory forest fires was developed by Alencar et al. (2004) for a study region near Paragominas in eastern Amazonia. That model operates at local spatial scale and at yearly time steps. It considers climate by analyzing ENSO and non-ENSO years, but concentrates on land-use and land-cover risk factors such as forest cover topology, logging, presence of roads and charcoal production. In the region studied by Alencar et al., the probability of understory fire was strongly associated to ENSO conditions and forest edges.

Nepstad et al. (2004) developed a basin-wide model for forest flammability. That model is driven primarily by plant-available soil water, which can be reduced by evapotranspiration and increased by precipitation. The model runs at 8 km spatial resolution and at monthly time steps. Applying that model to the period 1996-2001 Nepstad et al. found that nearly one third of forests in Amazonia were flammable during the dry ENSO conditions in 2001.

Cardoso et al. (2003) developed a model for fire activity in the Brazilian Amazonia, by relating satellite fire data to major large-scale factors for fires in the region. The model runs at 2.5-deg and yearly time steps, and considers land-use, land-cover and climate conditions. The model is able to reproduce the contemporary large-scale fire activity across the region, and was used to project future fire activity in response to potential future land-use and climate conditions, caused by planed development for the region. According to that study, future fire activity is likely to increase substantially in response to these changes, if the current relations between fires and land management hold true for the future.

## 3. Synergy between Methods

Fire research is an essential component of environmental studies in Amazonia. Fires have important influences on land and atmosphere and are strongly linked to the changing patterns of land use in the region. Different methods are used to provide information on fires occurrence, behavior and effects. They can be generally classified as ground-, remote sensing- and modeling-based methods. The synergy between methods is very important. For example, the frequent large-scale coverage provided by satellites allows for supplementing occasional small-scale data from ground-based studies. Local-scale ground-based data allow for building and calibrating fire models. Models are very important as unique tools for projecting future fire activity and effects.

There is a high interest on fire studies based on multiple methods, and providing information at small temporal and spatial scales and for large domains. Studies with these characteristics are desirable because they allow for robust conclusions based on results from multiple methods, and allow for expanding our knowledge on fires from interacting methods. In addition, the spatial and temporal scales in which they provide information are particularly important. Studies performed at small scales and presented in fire-impact units are easier to interpret. For example, ground-based data in units of area burned are easier to interpret than satellite-based fire pixels. On the other hand, it is difficult to measure fire properties at fine scales for large domains. This is a major reason why large-scale fire occurrence datasets from remote sensing expanded faster than small-scale ground based datasets on effects and fire behavior.

**Table 1.1 Reviewed fire studies**

| Method | Study | Spatial resolution ($km^2$) | Temporal resolution (day) | Spatial domain ($km^2$) | Temporal domain (day) |
|---|---|---|---|---|---|
| G | Nepstad et al. 1999 | 1 | 365 | 9160 | 365 |
| G | Cochrane et al. 1999 | 0.005 | 0.25 | 0.05 | 365 |
| G | Prins et al. 1998a | 0.0004 | 0.04 | 0.154 | 3 |
| G | Cardoso et al. 2005 | 0.0001 | 0.004167 | 50100 | 2.375 |
| G | Kaufman et al. 1992 | 0.1 | 0.020833 | 2.4 | 3 |
| G | Ward et al. 1992 | 0.1 | 0.020833 | 3 | 3 |
| G | Cochrane and Schulze 1999 | 0.005 | 30 | 100 | 30 |
| G | Uhl and Kauffman 1990 | 0.0002 | 1 | 3.5 | 191 |
| G | Kauffman et al. 1998 | 0.000075 | 0.083333 | 0.0072 | 3 |
| G | Hughes et al. 2000 | 0.000075 | 0.083333 | 0.35 | 6 |
| G | Carvalho et al. 2001 | 0.01 | 0.010417 | 0.17 | 60 |
| G | Fearnside et al. 2001 | 0.00006 | 1 | 0.17 | 60 |
| G | Guild et al. 1998 | 0.000075 | 1 | 0.118 | 3 |
| G | Miranda et al. 1996 | 0.000075 | 1 | 0.08 | 4 |
| G | Dias et al. 1996 | 0.000001 | 0.020833 | 3 | 90 |
| G | Turcq et al. 1998 | 4 | 120450 | 4 | 2555000 |
| G | Sanford et al. 1985 | 0.0001 | 66065 | 1.5 | 2190000 |
| RS | UW-CIMMS 2008 | 16 | 0.020833 | 3500000 | 3285 |
| RS | CPTEC 2008a | 1 | 1 | 3500000 | 7300 |
| RS | Justice et al. 2002 | 1 | 0.5 | 3500000 | 1095 |
| RS | Giglio et al. 2003 | 4.84 | 2 | 3500000 | 5.5 |
| RS | Gregoire et al. 2003 | 4 | 365 | 3500000 | 365 |
| RS | Kampeneers et al. 2002 | 1 | 365 | 3500000 | 365 |
| RS | Kaufman et al. 1992 | 10000 | 0.083333 | 1000000 | 7 |
| RS | Ferek et al. 1998 | 1 | 0.003472 | 19 | 0.329861 |
| RS | Andreae et al. 1988 | 2500 | 0.020833 | 3500000 | 20 |
| RS | Selhorst and Brown 2003 | 0.005 | 1 | 400 | 365 |
| M | Alencar et al. 2004 | 0.0009 | 365 | 3472 | 3650 |
| M | Nepstad RisQue | 64 | 30 | 3500000 | 2190 |
| M | Nepstad RisQue98 | 64 | 150 | 3500000 | 365 |
| M | CPTEC 2008b | 625 | 2 | 3500000 | 2555 |
| M | Cardoso et al. 2003 | 62500 | 150 | 3500000 | 9125 |
| M | Moorcroft et al 2001 | 0.000225 | 1 | 3500000 | 91250 |
| M | Van de Werf et al. 2003 | 10000 | 30 | 3500000 | 1460 |
| M | Potter et al. 2001 | 64 | 1 | 3500000 | 1095 |

Several characteristics of methods for fire research concentrating on their spatial and temporal scales are discussed as follows. From the studies reviewed, spatial resolution and domain (Figure 1.2) can be related to temporal resolution and domain (Figure 1.3). Some important patterns between resolution and domain are noticeable in both Figures 1.2 and 1.3. First, there is an empty upper left region. This region is “trivially” empty because there are no values of study domains that are smaller than their corresponding resolutions. Second, studies represented at the lower right (higher resolution and large domain) region are less common then studies with points organized along diagonal. One reason for this pattern is the difficulty to perform studies at fine resolution over large spatial and temporal domains. For example, it is difficult to perform ground-based burned area estimates in a large region before the vegetation recovers. Third, points from studies performed using similar methods are generally organized in similar spatial and temporal scales.

Spatially, the high-resolution region in Figure 1.2 is mostly populated by points from ground-based studies. At relatively lower resolutions, most points represent remote sensing- and modeling-based studies. Ground-based studies are less common at larger domains. Remote sensing and modeling methods had similar organization occupying mostly higher-domain and lower-resolution regions. Both methods were rare at resolutions smaller than one square kilometer.

Temporally, the higher-resolution region of Figure 1.3 is mostly occupied by ground-based and remote sensing-based studies. It is interesting that a ground-based study is represented at the lowest-resolution, largest-domain region. The reason is because that study represents the sediment records of fire activity, which can give information on fire occurrence at larger time domains, but low time resolution. Modeling studies were less common at higher resolutions. This pattern makes sense because model calibrations may rely on data aggregation, in order to reduce alignments errors between datasets used for calibration.

The spatial and temporal scales of the studies are also important for interpreting their results. For example, current large-scale satellite fire detections cannot be used to measure fire spread. The daily or two-daily fire detections made by polar orbiting satellites do not present a diurnal cycle reported in ground-based studies and geostationary satellites data. Fire pixels are the most common type of data on fire occurrence, but they cannot be converted directly to area burned or biomass consumed. At the same time, it is difficult to extrapolate detailed but irregular ground-based fire occurrence information to large spatial and temporal domains. Modeling-based studies are able to provide information at a wide range of scales and domains, but our confidence in their results depend on ground- or remote sensing-based data that can be used for validation.

One way to advance fire research is to use multiple methods. For example, associated ground- and remote sensing-based data can be used to improve the interpretation of remote sensing products. From these interpretation studies, fire occurrence datasets based on remote sensing could be adjusted to account for complicating factors for fire detection from space. The confidence on results from modeling studies benefit from calibrations and validations based on observational data from ground- and remote-based studies. Better models in turn can help planning ground experiments and remote sensing instruments where and when they are needed the most.

Interactions between similar methods can also be important. For example, hourly detections from geostationary satellite GOES show a daily cycle of fire activity that is consistent with information from ground-based studies, where most fires happen in the afternoon and fewer fires happen in the morning or at night. Fire detections from ASTER are made at spatial resolution significantly higher than the detections from GOES, but ASTER daily or two-daily overpasses produce data at significantly smaller temporal resolution. Together, ASTER and GOES8 datasets indicate that improved remote sensing fire detections could be achieved by sensors that have all these characteristics combined.

The potential for improvements in fire research can be also visualized by the relations represented in Figures 1.2 and 1.3. For example, as discussed above fire data from all methods at small resolutions and for large domains are of great interest. In hypothetical graphs similar to the ones in Figures 1.2 and 1.3, this situation would correspond to the points from all methods being at small temporal and spatial resolutions and at large domains. In other words, points in Figures 1.2 and 1.3 would be concentrated in the lower right portion of the graphs. However, those figures do not show this pattern.

Figures 1.2 and 1.3 show that different methods typically provide information at different resolutions and domains. In addition, the desirable high-resolution and large-domain region is not densely populated. Intermediate situations between the hypothetical ideal situation above and the actual patterns in those figures would be of interest. Greater overlap between methods would be of value. Greater overlap would make it easier to compare results, and would necessarily entail more data in the under-represented high resolution large domain region.

There are important challenges for combining multiple methods. First, as indicated by Figures 1.2 and 1.3, there are important tradeoffs between resolution and domain. The patterns in Figure 1.2 show that is difficult to extend high-resolution measurements for large spatial regions. Similarly, the patterns in Figure 1.3 suggest that is difficult to measure high-frequency data over long periods of time. These tradeoffs can be interpreted as “efforts” for performing fire studies. For example, it is laborious to collect fire occurrence data in a large region using a ground-based method. It is also challenging to produce geostationary sensors that can collect data at high spatial resolutions. Geostationary satellites are able to detected fires at higher frequencies than polar-orbiting satellites. However, geostationary satellites must occupy orbits that are further from the Earth surface where is more difficult to produce high spatial resolution imagery.

A second challenge is the need for multidisciplinary expertise. Studies based on combined methods would need personnel with multidisciplinary background. For example, field researchers may not be familiar with remote sensing or modeling. Similarly, modeling specialists may not be experienced with the implementation of ground-based field campaigns. The need for multidisciplinary collaboration was emphasized before as a way to advance in geosciences (IPCC 2001). The possibilities for improvement are promising given the increasing number of interdisciplinary research and academic programs, such as the International Geosphere-Biosphere Program (IGBP), and the Large Scale Biosphere-Atmosphere Experiment in Amazonia (LBA).

In all cases, resource availability can be an important obstacle for performing fire studies using multiple synchronized methods. There is need for additional individuals for planning, performing measurements, and analyzing data. Multiple methods may also require different types of equipment. For example, remote-sensing missions are very expensive. In the sample of studies reviewed, the majority of studies that applied multiple methods were part of larger campaigns such as ABLE-2A (Andreae et al. 1988), BASE-A (Kaufman et al. 1992), BASE-B (Ward et al. 1992) and SCAR-B (Prins et al. 1998), which required large budgets.

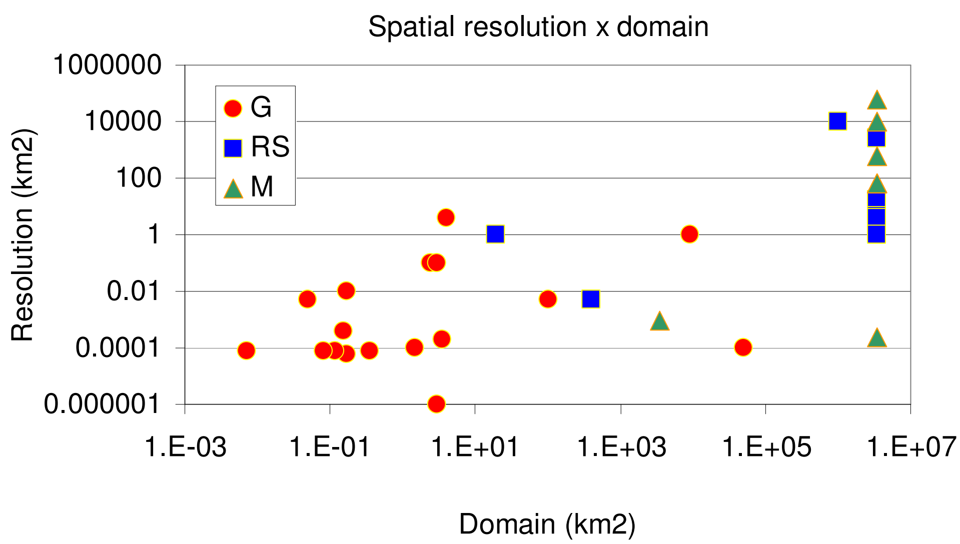


Figure 1.2 – Relation between spatial resolution and domain for ground-based (G), remote sensing (RS) and modeling (M) methods.

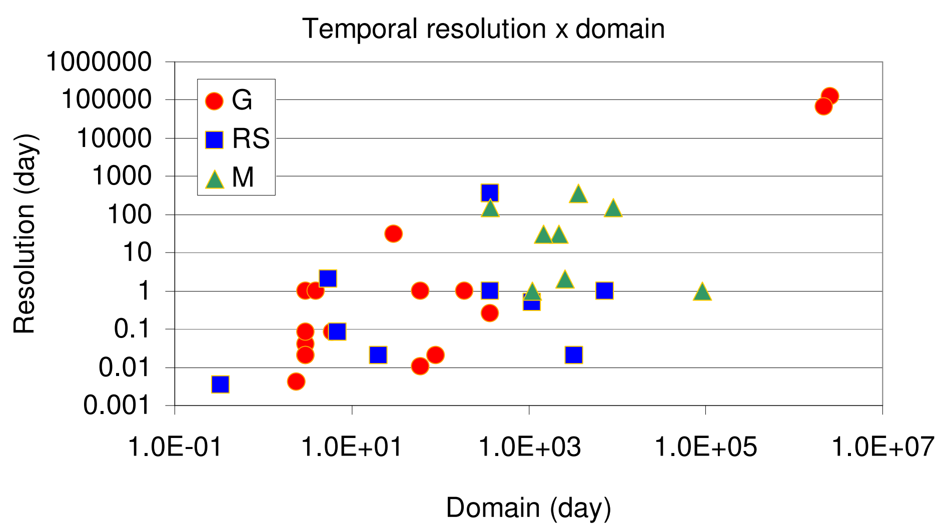


Figure 1.3 – Relation between temporal resolution and domain for ground-based (G), remote sensing (RS) and modeling (M) methods.

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## 4. Conclusion

Ideally, there would exist fire information from multiple methods at small spatial and temporal scales and for large domains. From the studies reviewed, however, it is found that different methods typically provide information at different spatial and temporal scales. In addition, an important tradeoff between resolution and domain can be identified both spatially and temporally. While ground-based methods can provide information at high spatial and temporal resolution, they usually do not provide data for large domains. On the other hand, remote sensing and modeling studies can provide information for larger domains but these data are usually at lower resolution, which complicate their interpretation for studying fires.

Studies based on multiple methods, and providing information at smaller scales and for larger domains would have a great potential for improving fire research. For example, studies collecting and analyzing coincident ground- and satellite-based fire data could improve the interpretation of current products and help designing future satellite fire sensors. Information from interpretation studies of satellite data would favor building and calibrating models. One of the most important outcomes from the synergy of multiple methods would be the possibility of building and validating a new class of models that would allow for applications at a wide range of scales and domains, such as from local-scale warning systems to ecosystem and climate/Earth System modeling.

While these combinations are highly desirable, there are important challenges for the future. Three main challenges have been identified. They include an important tradeoff between datasets resolution and domain, the need for multidisciplinary expertise and the need for resources. The potential for overcoming these challenges are promising because methodologies and technology for fire research are advancing, and the number of interdisciplinary academic programs is rising. However, progress will depend strongly on sustained or increased budgets for supporting relevant research.

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