THE FIRE COMPONENT OF GLOBAL OBSERVATION OF FOREST COVER: A PLAN OF ACTION

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Abstract

This paper provides a summary of a Global Observation of Forest Cover (GOFC) workshop on satellite observations of fires, and a plan of action resulting from that meeting. The meeting focused on the needs for fire information from various user communities, the capabilities of existing satellite-based fire-observing systems and the research and development needed to improve these systems. The objectives and findings of the meeting are presented together with the meeting recommendations.

A number of satellite sensing systems currently provide different information, including the location of active fires, burn scars, and vegetation characteristics. The development of algorithms and experimental products has occurred in the research domain, and some of these products are now being incorporated into prototype operational systems.

Combining data from the different sensing systems to provide enhanced information was found to be high priority, but this presents a technical and logistical challenge. Quantifying the accuracy of fire products is of great importance to the user community, and currently a high priority for the research community. Efforts are now being made to move the most effective proven techniques into the operational domain. Networks of researchers, data producers and fire information users are being established, making use of recent advances in Internet technology for data and information distribution. Even at this early stage, fire information from networks using earth-observation satellite data is being used to produce a much more current and complete overview of the global fire situation on a daily basis, notably through the Global Fire Monitoring Center.

Over the next few years, the GOFC Forest Fire Monitoring and Mapping initiative will undertake

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pilot projects and assist in the definition of requirements and specifications for the satellite component of a global observing system for fire monitoring.

This paper is presented in four sections: Background, Discussion, Recommendations, and Conclusions. Certain topics are repeated in subsequent sections, as this reflects the development of ideas before, during, and after the workshop.

Background

Integrated Global Observing Strategy

The Global Observation of Forest Cover program began in late 1997 as one of six pilot projects set up to test the concept of an Integrated Global Observing Strategy (IGOS). The IGOS concept is set out in Williams and Townshend (1998). It is:

- an initiative to develop a comprehensive strategy for enhanced levels of support to scientific, operational and research communities; and
- a strategy to enable agencies to better plan missions and activities;

The need for an IGOS arises out of the recognition that no single nation can satisfy all its observation requirements; contemporary data/information products often require the integration of multiple observations from multiple sources, and performance measures should be adopted with the aim of continuous improvement. If successful, the IGOS will:

- enable space agencies to plan earth observation projects with the minimum of unnecessary overlap, and to devise joint strategies for addressing serious gaps in their observation capabilities;
- achieve outcomes that are beyond the capabilities of existing systems;
- be the joint product of all the agencies involved;
- build on current achievements, with additional efforts being directed towards areas where satisfactory international arrangements and structures do not currently exist; and
- address the collection of both space-based and *in-situ* data.

The development and implementation of the IGOS is supported by a partnership (http://www.igospartners.org/). The IGOS partnership unites the major satellite and ground-based systems for global environmental observations of the atmosphere, oceans and land. The partners include the Food and Agriculture Organisation of the United Nations (FAO), the United Nations Educational, Scientific and Cultural Organisation (UNESCO), the Intergovernmental Oceanographic Commission of UNESCO (IOC), the International Council for Science (ICSU), the United Nations Environment Programme (UNEP), the World Meteorological Organisation (WMO), the program offices of the Global Ocean Observing System (GOOS), the Global Climate Observing System (GCOS) and the Global Terrestrial Observing System (GTOS), and the civil space agencies belonging to the Committee for Earth Observing Satellites (CEOS), the International Geosphere Biosphere Programme (IGBP), the World Climate Research Programme (WCRP),

and major national agencies funding global change research grouped in the International Group of Funding Agencies (IGFA).

Provision of global observations in an operational sense, rather than research-oriented, is currently the remit of the three global observing systems sponsored by various UN organizations. The Global Terrestrial Observing System (GTOS) aims to provide policy makers, resource managers and researchers with the data they need to detect, quantify, locate and understand changes (especially reductions) in the capacity of terrestrial ecosystems to support sustainable development. However, technological, institutional, and funding limitations impede rapid progress towards this objective.

GOFC has identified users of forest information at national, regional, and global levels. These include government and private forest management services, NGOs, research programs (mainly dealing with global change) and international organizations (FAO, UNEP, and the environmental conventions' secretariats). Gaps in currently available global forest information were identified with regard to forest cover change, resource inventory, and fire. International teams prepared strategies for product creation and dissemination. GOFC has reached a strong consensus with users of forest information and suppliers of earth-observation data that routine operational observation of forests worldwide is an urgent priority. The GOFC program aims to provide long-term global forest information in a sustainable and sustained manner.

The Forest Fire Monitoring and Mapping component of GOFC

Forest Fire Monitoring and Mapping was identified as one of the three primary components of the GOFC Strategic Plan (Ahern *et al.*, 1998). The three components are:

- Forest Fire Monitoring and Mapping
- Forest Cover Characteristics and Changes
- Forest Biophysical Processes

These components are being pursued individually because each presents unique challenges in terms of user requirements, data types, data volumes, data processing, and institutional and funding arrangements that must be put in place. Thus, it is envisioned that the three components will move toward operational implementation at different rates. During the implementation of GOFC, communication between the three components will take place to ensure that the benefits to be achieved through cross-linkages and sharing common technologies are achieved.

The Forest Fire Monitoring and Mapping component (hereafter referred to as GOFC-fire) has a number of unique characteristics which distinguish it.

For forest fires, and indeed all wildland fires, much useful information can be produced using data from coarse resolution sensors (in GOFC, we use coarse resolution to mean a resolution greater than 100 m and fine resolution to mean a resolution finer than 100 m). These sensors provide smaller data volumes than

fine resolution sensors, which results in simpler data handling, processing, and dissemination, and thus, lower cost. Additionally, most of the data used to date has come from meteorological satellites, which is available at a relatively low cost per square kilometer.

Considerable experience has been obtained for both active fire monitoring (Li *et al.*, this volume; Kaufman *et al.*, 1998) and burn scar mapping (Arino *et al.*, this volume). Robust algorithms have been demonstrated which are capable of producing acceptable results over large regions and even globally (Dwyer *et al.*, 1999). Pre-operational demonstrations have taken the state of the art beyond the research phase to include the development of institutional networks, together with data networks to disseminate products and results. Particularly as a result of the large number of extreme fire events that occurred in 1998, there has been and continues to be strong interest in reliable wide-area and global wildfire information, and a number of organizations have begun to collect, analyze, and interpret information about wildfires from earth observation data and other sources. Finally, it appears reasonable to expect that the operators of meteorological satellite systems will be willing to incorporate wildfire products into their product suites if they are convinced that the products are accurate and reliable, and that there is a strong demand for them.

GOFC-Fire workshop

During the GOFC design phase, it was apparent that many of the pieces of the complete picture were available, enabling GOFC to determine how they could be brought together, and recommend specific actions to make this happen. To accomplish this, a workshop was convened on November 3rd–5th, 1999. The workshop was hosted by the Space Applications Institute of the Joint Research Centre of the European Commission, in Ispra, Italy.

Very briefly stated, the workshop plan was to:

- review and document user requirements;
- review and document the existing capabilities to build upon. These include technical considerations (such as sensors, algorithms, products, validation, existing communications and distribution networks), as well as existing institutional capabilities and arrangements which could be modified or expanded; and
- recommend actions to produce clear progress toward the ultimate objective of routine, on-going observations and the production and dissemination of products, with full involvement of users at all stages of the endeavor.

This chapter documents the discussions and recommendations of the workshop. For completeness, it provides a brief summary of user requirements and the technical state of the art at the time of the workshop, as background. However, these subjects are reviewed much more completely by the key researchers and user agency representatives in the remaining chapters of this volume.

User requirements

In designing the GOFC fire component, three categories of users were considered: the global change research community, policy and decision makers, and fire managers. Reports summarizing the needs of each of these groups have been written for this volume. They are briefly summarized under the heading 'Relationships with users' in both the Discussion and Recommendations sections of this chapter.

Existing capabilities to build upon

The current capabilities and experience provide an excellent foundation to build upon. The highlights are reviewed here; readers are referred to other chapters in this volume for a complete review of each topic.

Thermal sensors capable of detecting active fires can provide data for the earth's entire land surface two to four times per day from polar-orbiting satellites (principally AVHRR on NOAA) (Kennedy *et al.*, 1994; Stroppiana *et al.*, 1999). Reception facilities for full-resolution data can now be obtained at low cost, and there are no fees or other restrictions on the reception of these data. Geostationary satellites can provide information on active fires every 15-30 minutes, allowing for the detection of short-lived fires and diurnal calibration of fire products from polar orbiting satellites. However, the spatial resolution of geostationary sensors is a limiting factor in detecting small fires (Prins and Menzel, 1996, Prins *et al.*, this volume). Several algorithms have been developed and validated for the detection of active fires (Li, *et al.*, this volume; Kaufman *et al.*, 1998; Giglio *et al.*, 1999), although there remains a need to reduce the rate of errors of omission and commission, and to document the types of error for the user. The visible wavelength Operational Linescan System (OLS) on the Defense Meteorological Satellite Program detects active fires at night and provides a valuable supplement to thermal detection (Elvidge *et al.*, 1996 and this volume). The two MODIS sensors to be launched as part of NASA's Earth Science Enterprise will provide improved active fire monitoring capability (Kaufman, *et al.*, 1998).

Several coarse resolution sensors hold promise for global mapping of burned areas: VEGETATION on SPOT, ATSR on ERS-1 and –2, AATSR on ENVISAT, MODIS on NASA's Terra and Aqua missions, and the Wide Field Imager on CBERS. Experience with these sensors is limited, but early results are very promising. Burn scar mapping of large fires has been demonstrated with AVHRR, but the relatively poor geometric, radiometric, and spectral properties of this sensor limit the precision and accuracy of such products (Roy *et al.*, 1999; Arino *et al.*, this volume). Robust automated methods for burn scar mapping have yet to be fully developed for all ecological regions of the earth.

Burned areas can be readily mapped with fine resolution sensors (*e.g.*, TM and ETM+ on Landsat; HRV and HRVIR on SPOT) (Chuvieco and Congalton, 1988; Pereira and Setzer, 1993), but at present the cost and complexity of data acquisition and processing prevent these data from being used for regional and global

products. However, these data provide an excellent means to validate the products produced by coarse resolution sensors.

This collective experience provides the community with an opportunity to participate in the design, development, and exploitation of future missions. NPOESS will provide environmental information based on the experience gained with AVHRR, OLS, and MODIS. The BIRD, FOCUS and FFEW/FUEGO initiatives are intended to lead to a constellation of satellites for rapid detection and response (Oertel *et al.*, this volume).

As the ability to produce information products (such as active fire locations) has matured, a number of formal and informal networks has been established to provide the information to users quickly, efficiently, and in an appropriate format (Grégoire *et al.*, this volume). It is the intention of GOFC to promote the development of such networks, with an ultimate goal of making global active fire and burn scar information available over the Internet, without restriction. Most of the networks established to date have utilized data from a single sensor. There is a need to work toward technologies which will bring data from multiple earth observation sensors, and other sources, together to produce superior information products.

In order to provide information for policy makers, particularly at the global level, considerable synthesis of information and analysis of its significance is needed. Organizations such as the Global Fire Monitoring Center (GFMC) hosted by the Max Planck Institute for Chemistry at the University of Freiburg, have been established to perform this role, and can provide considerable guidance regarding information requirements at the global level, and thus influence the development of sensors, information extraction algorithms, and distribution networks (Goldammer, this volume).

Discussion

Relationship with users

One of the lessons learned from early experience in developing practical applications of remote sensing technology is that the best success is obtained through the active participation of the end user at all stages of development, from sensor design through product development, to operational demonstrations and operational implementation. Unfortunately, many remote sensing endeavors still fall short in the degree to which they involve users.

The GOFC Forest Fire Monitoring and Mapping workshop had excellent user involvement, with approximately 50% of the participants representing various user communities. There was much discussion regarding the types of users, their needs, and how these needs can best be satisfied. There was also discussion of the institutional relationships that exist, and how they should be modified.

In general, the participants were comfortable with the three user communities that the organizing committee identified for planning purposes: the global change research community, the fire management community, and policy and decision makers.

Fire managers

The needs of the fire management community are rather diverse and include fuel types, fuel condition (which is normally inferred from fuel type and weather information), location of ignition events (particularly lightning strikes), location of fires, fire intensity, rate and direction of fire spread, smoke, and post-fire damage assessment. Many of these information requirements have also received attention from the Wildland Fire Hazard Team of the CEOS Disaster Management Support Group, (DMSG-Fire), particularly fire detection for rapid response, and post-fire damage assessment. It is important to point out that GOFC is not attempting to address the requirement for nearly instantaneous fire detection needed for rapid response by control teams. Indeed, DMSG-Fire was established by the IGOS partnership to address this need. Both GOFC and DMSG-Fire recognize the need for these two organizations to pursue clearly-defined objectives and avoid duplication. This has been accomplished through frequent communication and by cross-membership in the two groups. Six members of the DMSG-Fire, including its chairman, participated in the GOFC workshop. It became evident during the workshop that it is also important for the IGOS projects to present a 'seamless' interface to fire users. Users need to make their needs known and be assured these needs will be addressed, without undue concern over which IGOS project is responsible. By having strong representation by DMSG-Fire, and through presentations regarding proposed fire detection missions such as BIRD, FOCUS, and FFEW/FUEGO, we believe that the GOFC workshop satisfied that need. The needs of the fire management community are discussed in greater detail by Dull and Lee (this volume).

Global change research community

The global change research community requires information on the location and timing of fires, maps of the area burned, and characterization of the fuel and combustion conditions, in order to understand and model the emissions of aerosols and trace gas. The location of active fires and annual maps of areas burned also serve as an important indicator of land use change, especially tropical forest conversion. Using models and other input data, fire products can provide essential information on ecosystem disturbance and recovery, and fire effects on biogeochemical cycles, particularly the carbon, nitrogen, and water cycles. They are also important for accurate modelling of the land surface radiation budget. It is expected that individual nations will want operational versions of these products in order to meet their carbon emissions reporting requirements under the United Nations Framework Convention on Climate Change.

The workshop served to clarify the frequency requirements for products which map burn scars and estimate fire intensity, damage and emissions. Annual summary products provide a useful and achievable early goal, but time-series products are required throughout the burning season in order to capture seasonal dynamics and ephemeral burn scars, and to calculate emissions. Coarse resolution data are considered sufficient for regional to global scales. Long observation times are necessary to document and understand inter-annual to decadal variations. Thus, the global change research community has a particular interest in the effective archive and retrieval of historical data, and methods to intercalibrate data from successive sensors with changing characteristics. Frequent monitoring of active fires throughout the day is needed for models of emissions.

The needs of the global change research community are discussed much more fully by Justice *et al.* (this volume).

Policy makers

The exceptionally large number and size of forest fires in Siberia, South-East Asia, and North and South America in 1998 brought unprecedented global attention to the issue of biomass burning. There was much discussion at regional and global levels, which underlined the need for greatly improved, objective information. Data from the AVHRR were used to provide regional overviews of active fires and smoke plumes, against an overall view of the area affected. Data from geosynchronous satellites were used to monitor large fires and track the movement of large masses of smoky air. However, differences in processing algorithms and methods resulted in confusion due to differing rates of omission and commission errors in hot-spot detection, as did differences in the portrayal of smoke plumes and the land surface background. In some cases, incorrect inferences were made through inadequate understanding of the nature of the data and limitations of derived information products.

Policy makers require consistent information with known and well-documented error rates. The workshop confirmed that accurate and well-documented daily global maps of active fires and annual maps of burned areas would be of great value to policy and decision makers. Accurate estimates of aerosol and gas emissions from all large fires would provide considerable additional benefit, particularly for climate change and human health considerations.

The workshop served to highlight the important role played by organizations that collect and analyze data and synthesize information about fires from diverse sources.

The needs of the policy makers are described in detail by Goldammer (this volume).

Similarities and differences

It is useful to recognize the similarities between the requirements of the three user groups from the perspective of the information that can be obtained from

earth observation data. These include vegetation characteristics (canopy type, density, and height), vegetation condition and fire susceptibility (often related to observable greenness), location, duration, and intensity of active fires, areal extent of damage, and post-fire vegetation condition. Starting with these observables, it is possible to produce products useful for each of the three user groups. However, we must also recognize important differences in requirements for timeliness, scale and accuracy, and speed of information delivery, which must be addressed to satisfy the requirements of each community.

User feedback

Improvement of information systems based on user feedback is essential, and has been recognized in the design of the Integrated Global Observing Strategy (Williams and Townshend, 1998). This reality was underscored at the workshop. It was recognized that the formation of regional and global networks of institutions to pursue a common objective (such as the World Fire Web, or the GOFC regional networks) provides an excellent mechanism for this feedback, through, for example, annual meetings of representatives from all of the nodes of a network.

The cost issue

The participants, particularly those representing user agencies, emphasized that cost is still an issue. Generally speaking, users have little interest in receiving raw satellite images. Instead they want derived information products. Recent technology, particularly the Internet and powerful yet inexpensive desktop computers, enable agencies to participate with a much smaller investment than ever before. The participants recommended that, as a pilot activity, GOFC should promote a fire component based on free sharing of data and information, at least in the short term.

Developing countries

Throughout its design and early implementation phases, GOFC has made a special effort to ensure the participation of developing countries. The participants recommended that GOFC-Fire should be instrumental in capacity building and technology transfer to developing countries. The increasing importance of the Framework Convention on Climate Change will affect developing as well as developed countries. The participants recommended that GOFC-Fire should provide information to support develop.ng countries in improving fire management and in implementing Green House Gas inventories in a consistent and lucid manner.

Political sensitivities

Several participants described some of the political sensitivities of fire information. If national agencies are to participate in international initiatives that involve the production and dissemination of fire information products, they must be able

to express confidence both nationally and internationally that the products are of the highest possible quality, with known and clearly documented accuracies and sources of error. The products must not be misleading or be used in a misleading way. Examples were given of situations where fire information products were misused (such as calculating the area burned directly from counts of hotspot pixels), and how such misuse caused political harm by creating false impressions and misguided pressure.

Documentation and standards

The need for validation activities, characterization of product errors, and clear, accessible documentation of product characteristics, was a recurring theme expressed by all users. This is clearly an important role for GOFC, aided by the CEOS Working Groups on Calibration and Validation, and Information Systems and Services.

Regional networks

Although participants endorsed the need for global fire products, the consensus was that improved products may be generated through regional efforts, where the regions generally cover a limited range of ecosystem types. This enables organizations to cooperate regionally to fine-tune algorithms and product delivery mechanisms to serve regional needs. The GOFC tropical networks follow this model, and the workshop participants recommended that the fire component be included in the scope of these and any future GOFC networks.

Infrastructure: technical and institutional

Achieving the ultimate objective of on-going operational observations and product delivery will require an infrastructure consisting of the technical means to exchange data (including meta-data), products, product documentation, and technical communications (e-mail and documents). It will also require an institutional infrastructure to facilitate communications and decisions at managerial and policy levels in order to ensure that the necessary organizational, human, and financial resources will continue to be available. Both the technical and institutional infrastructure needs were discussed at the workshop.

An important GOFC principle was strongly reiterated at the workshop: to build on and strengthen existing organizations and networks, including improved collaboration among them, and to avoid initiating new structures unless absolutely necessary.

Technical infrastructure

It was recognized that the Internet provides the basic communications infrastructure necessary to accomplish a large proportion of the Forest Fire Monitoring and Mapping objectives of GOFC. The Internet enables participants to exchange e-

mail messages, documents (usually as attachments), and modest quantities of satellite data. Most visibly, it enables participants equal access to a wide variety of information products if they are 'posted' on a website. In addition, GIS technology is now becoming available on the Internet which enables users to merge data from multiple sources, analyze the resulting products, and make them available in forms most suitable for interpretation and decision making by resource managers. Thus, full Internet connectivity was identified as being highly desirable, if not essential, and a goal which GOFC should advocate for each organization that will participate in advancing the fire component.

The participants recognized that the World Fire Web provides an initial institutional network linking suppliers and users. It provides a mechanism to obtain feedback on the utility and shortcomings from users to suppliers. It can be organized into regional sub-networks which can share commonality with GOFC regional networks. It provides a mechanism for contact between algorithm developers and users, and a rapid and inexpensive means of transfer of technology to developing countries. However, it was also recognized that additional resources are needed to truly build local capacity in developing countries, both to use the technology and particularly to make best use of the results. GOFC should provide advocacy for this necessary increase in the capacity of developing countries to manage fire information. The World Fire Web also provides a means for development of regional algorithms which can be shared and compared globally.

Institutional infrastructure

The Global Fire Monitoring Center provides an 'overview user' perspective which participants found very useful. It provides a connection between earth observations and policy makers. It demonstrates the need to synthesize information from multiple sources, not all of which are geospatial, to provide insights for policy makers. It can also provide valuable feedback regarding the utility of various kinds of information. For example, although daily active fire ('hotspot') products cannot be used for fire management or even to estimate the area burned, they do bring attention to severe multiple fire events and enable national and international decision makers to have access to similar data. This can contribute greatly to the regional and global dialogue, which can lead to changes in national and international policies. The participants recommended continuing and increased interaction between GOFC and GFMC, and linkages with a number of existing international fire-related organizations, including the World Meteorological Organization (WMO), the World Health Organization (WHO), the follow-up arrangement of the International Decade for Natural Disaster Reduction (IDNDR), the United Nations Environment Programme (UNEP), United Nations Educational, Scientific and Cultural Organization (UNESCO), the International Union of Forestry Research Organizations (IUFRO), the International Boreal Forest Research Association (IBFRA), the International Tropical Timber Organization (ITTO), the World Bank ProVention Consortium (Consortium on Natural and Techno-

logical Catastrophes), the World Conservation Union (IUCN), the Worldwide Fund for Nature (WWF) FIREFIGHT program, and programs with regional significance, *e.g.*, PROARCO in Brazil or PARTS in the Association of South East Asian Nations (ASEAN).

Building upon what already exists, the participants urged GOFC to help develop or promote a network of key organizations and agencies involved in providing, collating, disseminating and using fire data, and to identify potential contributions to national, regional and global syntheses on fire.

Research and algorithm development

The discussion identified differences between some researchers who want to move on to research leading to new fire products, and a need, strongly expressed by users, to validate and improve existing systems so that they will be reliable and acceptable. The consensus was that many active fire products achieve useful accuracy, but that the accuracy needs to be clearly validated and documented (Giglio *et al.*, 1999). Immediate priorities include improving active fire detection algorithms through regional optimization, and minimizing and documenting rates of omission and commission error for each algorithm that is used to produce demonstration or operational products. Over a slightly longer time-frame, priority should be given to developing algorithms that use well-calibrated data and physical knowledge rather than empirical algorithms which must be re-calibrated for each new sensor and for different regions and conditions. Another priority is to ensure that products are produced and delivered with information, formats, and delivery mechanisms that truly suit the needs of particular end-user communities.

The development of burn scar products is less advanced than the development of active fire products, but the researchers seemed confident that automated algorithm development and validation of products would progress smoothly and rapidly, making possible the production of regional and global demonstration products. High priority should be placed on the development of algorithms for automated burn scar mapping with SPOTVGT, ATSR, and MODIS. Important research issues include determining the sensitivity to land cover and its properties, compensating for the directional properties of the surface and sensor viewing geometries, quantifying the confusion resulting from vegetation removal due to other means than burning, and determining the error in the estimation of burned areas as a function of size and shape.

It was agreed that both active fire products and burn scar products can be made more accurate by using multi-date data. It was also agreed that priority must be given to the research and development (R&D) necessary for producing new products, particularly fuel loads, fuel condition, severity of burn, and aerosol and trace gas emissions. The first step is to define the specifications of these advanced fire products through a continued dialogue with users via GOFC, CEOS DMSG-Fire, and other agencies. This could be done starting with existing docu-

mentation, producing draft specifications, and revising and completing these using a community electronic forum.

Based on the large experience currently available (Justice, 1999 and this volume; Arino *et al.*, this volume; Elvidge, this volume; Grégoire *et al.*, this volume; Li *et al.*, this volume; Pereira *et al.*, this volume; Prins *et al.*, this volume), it is apparent that data from many of the current and planned sensors can provide complementary information. Thus, products derived from multiple data sources can be expected to have a greater information content and be more accurate than products derived from data from a single sensor. There was considerable discussion of the opportunities and challenges of multi-sensor integration and the combination of satellite data with other geographic data sets. The consensus was that there is a need to move forward in algorithm development, and also in the development of institutional and technical infrastructure to facilitate multi-sensor integration. In addition to algorithm development, challenges include institutional and communications linkages to bring data from multiple sensors to a single work station, and the ubiquitous challenge of geometrically correcting and resampling all the data to a common base map grid.

The participants agreed that the most effective mechanism to address these challenges is through a series of demonstration projects (see Demonstration projects section).

Although AVHRR data are not ideal for burn scar mapping, and results to date have been mixed, the AVHRR provides the only global historical record of biomass burning. Therefore, some effort should be placed on developing and validating reliable automated algorithms for multi-year burn scar mapping with AVHRR data, addressing the need for precise registration, and compensating for changes in the characteristics of the AVHRR sensors on successive NOAA satellites. A rigorous comparison between burn scar maps produced from AVHRR with the same products for the same areas produced with data from more advanced sensors will provide important validation information.

Although a suite of regional efforts allows for algorithms tailored to a given range of conditions, it was recognized that global algorithm development is needed. This can serve as a basis of comparison between regions and with regional algorithm development. One approach which was recommended was to generate global and regional products with both single and multiple algorithms, with the aim of having a global algorithm parameterized for different regions.

With the current high interest in wildfires and the carbon cycle, there did not seem to be serious concern about finding the resources necessary to carry out the new R&D while still improving existing algorithms.

Validation

Validation of fire detection algorithms is difficult, since it requires experiments to be carried out during active fires, including simultaneous ground or airborne

observations. The research community can only afford a few 'active fire' validation experiments, rendering it logistically difficult to obtain sufficient independent data. Wide participation is needed to make the most of these opportunities. Validation of burn scar area mapping is somewhat easier. Data from fine resolution satellites provide a useful source of validation information. Care needs to be taken to ensure that adequate fine resolution data are acquired over the validation period and that the accuracy of the fine resolution products themselves is quantified. Users should be involved in validation exercises, because they often have a more detailed understanding of the fire characteristics in their region than remote sensing researchers from other countries. This will enable users to understand the limitations of the products they intend to use.

The participants strongly recommended the establishment of a global network of active fire and burned area validation sites. These sites, representative of a range of global fire conditions, would provide common data sets for accuracy assessment of products from different sensors and their comparison. The Land Product Validation sub-group of the CEOS Calibration and Validation Working Group provides an important forum for this new development. Accuracies derived from validation exercises must be documented clearly and very visibly with the corresponding products. The first step is to develop consensus active fire and burned area product validation approaches and identify sources and protocols for the collection of independent validation data. It will be also be necessary to develop and document consensus data pre-processing and quality assessment procedures and consensus reporting protocols.

Demonstration projects

Demonstration projects that include the active involvement of end users and that include a modest development component provide an excellent mechanism to progress rapidly in a coordinated fashion at global and regional levels. They also provide an excellent mechanism for user feedback. Three areas were identified for GOFC demonstration projects:

- Expand the World Fire Web active fire product to global coverage, while decreasing the turn-around time from one week to one day.
- Create and distribute burned area demonstration products. Supplier representatives indicated that regional to global scale annual products could be achieved in one to two years with data from three sensors:
  - SPOT-VEGETATION; to be produced by the Joint Research Centre Space Applications Institute and made available through the World Fire Web;
  - ATSR; to be produced by ESA/ESRIN; and
  - MODIS; to be produced by the NASA/MODIS fire team.
- Multi-sensor integration: develop a demonstration project, integrating data from geostationary and polar-orbiting satellites, in order to detect active fires and develop multi-sensor burn scar products for selected regions of the world.

Suggested regions covering numerous vegetation types were eastern Asia, Australia, and Africa. Sensors to be included were NOAA/AVHRR, DMSP/OLS, ATSR, MTSAT (next generation Japanese geosynchronous satellite), SPOT-VEGETATION and MODIS. These should be augmented with high resolution data for burned area validation. There are several initiatives in these regions which could be brought together in this endeavor.

The user interface for global fire products needs further development. It is recognized that GIS functionality is essential. One approach which has been successfully demonstrated uses 'Map Server' software, which provides basic GIS capability through the supplier's server, thus removing the burden on the user. It was agreed that the WFW should explore this approach. The CEOS WGISS Test Bed Facility provides a forum for developing the technological advances needed for these demonstrations (McDonald *et al.*, 2000).

Continuity

Two aspects of continuity were discussed at the workshop. Making progress from the present to the future requires well-considered planning for R&D and algorithm development, and planning preoperational demonstrations with current sensors. Interaction is needed with the space agencies and other supplier organizations to ensure that future operational missions, such as NPOESS, METOP, and the international suite of geostationary satellites will provide the data and information products that have been defined, developed, and refined through GOFC and other endeavors.

User advocacy for data continuity is essential in moving toward a demand-driven system. If users and suppliers can work together to develop end-to-end technology which meets real needs, and if users can continue to make their needs clearly known internationally, it would not seem exceptionally difficult to create operational sensors and ground systems by augmenting plans and systems currently under consideration and development by CEOS member agencies.

At the same time, global change research requires the means to assure that accurate, reliable long-term data and information products are secured and made available. Gutman *et al.* (this volume) review the archive of geosynchronous and polar-orbiting environmental satellite data held by US agencies, which is the most complete archive for these purposes. Advances in computer technology are making it possible to secure this archive and make it available on-line. Unfortunately, the only complete global AVHRR archive contains the 4-km resolution Global Area Coverage (GAC) data since 1978; 1-km Local Area Coverage (LAC) data are rather incomplete. The GAC data have been shown to miss many fires (Belward *et al.*, 1994; Eva and Lambin, 1998). However, it is felt that inter-calibration of products made with LAC and GAC data could be used to remove the underestimation bias statistically, and to produce a 20-year global fire history with known accuracy (Gutman *et al.*, this volume). In addition to the R&D challenge of producing

reliable historical products, an associated issue is the cost of reprocessing the historical data. This issue was not discussed at any great length at the workshop, but it is reasonable to expect that technological advances which are making it possible to make the data archive available on-line will also make it possible to re-process the needed data at an affordable cost.

Recommendations

For the purposes of clarity, the workshop recommendations are presented in two categories: general and specific. The general recommendations are programmatic in nature, covering many or all aspects of the GOFC-Fire component. These were formulated following considerable discussion in the plenary sessions of the workshop. The specific recommendations were put forward by the individual breakout groups; while they were also reviewed in the plenary sessions, the discussion was more limited.

General recommendations for the GOFC-Fire component: mandate, mission, and implementation

- The transition of successful experimental projects and products to the operational implementation must be ensured. The recommended GOFC-Fire approach is to undertake preoperational demonstration activities, which include the development, testing, and validation of prototype operational algorithms and products, the development and implementation of networks for data and information, and preoperational testing on a 'pilot' basis. All these steps should be undertaken through the joint efforts of users, researchers, and suppliers.
- GOFC-Fire must ensure that fire monitoring observational requirements are considered in the design of future operational satellite systems such as NPOESS and METOP, and that fire information products such as detection and mapping of active fires, burn scars, and estimates of aerosol and gas emissions, are provided operationally. GOFC must maintain its links with CEOS and IGOS in order to effectively lobby on behalf of the fire community.
- GOFC-Fire will serve as a forum for the review and improvement of fire products (active fires, burn scars, and other fire signatures) information, and take a lead role in providing satellite-derived information related to ecosystem stability and atmospheric chemistry, notably the global carbon cycle and air pollution affecting human health.
- GOFC-Fire will provide a framework for multi-sensor calibration/validation, including the identification of a global set of long-term observation sites for fires. It should encourage participants to take advantage of ground-based and airborne fire experiments to test and validate new satellite products.
- GOFC-Fire should support the maintenance of historical ('heritage') Earth

Observation data, and help make best use of these archived data to support long-term studies of fire frequency and fire history.

- Programs such as MODIS, BIRD, SPOT Vegetation, ATSR and the planned FOCUS instrument on the International Space Station (ISS), as well as satellites such as FUEGO and others, must be used and supported to help define, document, and implement long-term fire observational requirements.
- GOFC-Fire will organize itself into an implementation team consisting of representatives from the various GOFC-Fire projects and regional networks and carry out the following activities:
  - meet once per year to track progress of the GOFC-Fire component and formulate new tasks;
  - form sub-working groups as needed, for example, to conduct algorithm intercomparisons for different ecosystem and sensor types, or to identify user requirements and develop specifications for operational sensors and products;
  - utilize established printed media and Internet networks for information dissemination (for example, the Global Fire Monitoring Center (GFMC) Internet information system and the UN-International Forest Fire News (IFFN)).

Relationship with users

Guiding principles

The user community should play an active role in defining fire product requirements and suggesting effective means of dissemination. Users should be involved in product development, implementation, and assessment. It is imperative that the users understand the limitations and potential of fire products by becoming actively involved in product validation efforts, and through reliable, up-to-date documentation that is made readily available for all products. Feedback in the form of shared experiences with respect to fire product usage is vital. User advocacy for data and product continuity is essential in moving toward a demand driven system.

General recommendations

- GOFC-Fire is targeting three key user communities: global change researchers, natural resource managers, and policy makers. GOFC-Fire should invite participation and inputs from these groups.
- GOFC-Fire should encourage widespread, low-cost and rapid access to satellite observations for use in fire monitoring and mapping.
- GOFC-Fire should work with developing countries to help quantify the distribution of fire and its impact on ecosystems and human society.
- GOFC-Fire should provide a forum for summarizing and synthesizing of fire data for the user community by using existing networks, notably the Global Fire Monitoring Center (GFMC).

Specific recommendations

- Encourage countries to establish mechanisms for collating information on fire and assessing its significance.
- Institute or promote a process for identifying potential users and uses of fire information at national, regional and international levels.

User feedback

- GOFC should help stimulate a user base to encourage the development of global and regional fire products.
- GOFC should help users to evaluate various types of satellite products and locate data providers.

The cost issue

- GOFC should promote a fire component based on free data during its pilot demonstration project phase. It is understood that operational data suppliers will need to recover costs, but these costs should remain affordable to fire information users.

Developing countries

- GOFC-Fire should be instrumental in promoting appropriate technology transfer of satellite-based fire mapping and monitoring techniques to developing countries and provide the means for developing countries to:
  - implement Greenhouse Gas inventories in a consistent and transparent manner; and
  - develop improved fire management systems.

Documentation and standards

- GOFC-Fire should work to:
  - document the advantages and disadvantages of different sensors and products from a user perspective, especially the limitations of the existing low-resolution sensor products;
  - make this information widely available, through the Internet, GFMC and other channels; and
  - develop metadata and product standards for regional networks, in order to help develop consistent data records and facilitate product intercomparison.

Regional networks

- GOFC-Fire should build on the emerging regional networks and utilize the experience gained through previous satellite fire projects.
- GOFC regional networks should be made aware of the GOFC Fire Component, to help coordinate regional activities.

Institutional infrastructure

GOFC-Fire should build on and strengthen existing centers and networks, promoting improved collaboration among them, and avoid initiating new structures unless absolutely necessary.

- Recognizing the complementary goals between GOFC and the CEOS Disaster Management Support Project DMSG-Fire group, common data sources and joint initiatives should be shared where appropriate. A GOFC representative

should be invited to all DMSG-Fire meetings, and a DMSG-Fire representative should be invited to all GOFC-Fire meetings. The two groups should work together to:

- ensure each component pursues clearly-defined objectives with a minimum of gaps and overlaps in the overall effort;
- address user needs as seamlessly as possible, especially from the user perspective; and
- identify common requirements and specifications for future sensing systems.

- The GOFC-Fire group should seek additional close cooperation and partnerships with the UN and other international organizations, as well as NGOs. These organizations should be informed of GOFC-Fire activities and products, and feedback solicited. This should lead to mutually-beneficial cooperative activities. For example, GOFC-Fire could address fire damage assessment with the Food and Agriculture Organization (FAO) Forest Resources Assessment (FRA). Cooperation should also be sought with the fire research and other relevant programs of international science organizations, for example, IGBP and START.
- Recognizing the need for continuing and increased cooperation among the various international agencies concerned with fire, GOFC-Fire supports the establishment of an international interagency fire working group. The new Working Group Wildland Fire under the Interagency Task Force for Disaster Reduction of the UN International Strategy for Disaster Reduction (ISDR) is considered a suitable candidate platform.

Technical infrastructure

- Full Internet connectivity (in both developed and developing countries) is necessary to carry out the exchange of information, data and product transfer and information access.
- Information products should be provided within a GIS framework, as this provides users with basic tools, such as zoom, roam, and overlaying user-specified map layers.
- GOFC-Fire endorses the expansion of the of the World Fire Web network, implemented by the EC Joint Research Centre, to global coverage with a 24-hour turnaround time, initially using NOAA AVHRR data. Over time, it should expand to incorporate future technology, and help regional nodes to choose and improve fire detection algorithms.
- Improved data management and delivery systems are needed to provide access to and delivery of fire information with special attention to the near real time (<24 hours) delivery of active fire products.

Research and algorithm development

General recommendations

- Enhance existing fire products to meet the needs of a broad range of users (*e.g.*, global change, fire management, and policy/decision makers.

- Develop physically based automated algorithms for fire monitoring and burn scar mapping.
- Develop algorithms that take advantage of additional information contained in multi-temporal data, *e.g.*, from data acquired before and after a fire.

Specific recommendations

Active fire products

- Improve automated fire detection algorithms for AVHRR, GOES, MSG, GMS, MTSAT, and DMSP/OLS:
  - develop techniques for differentiating fire areas from cloud shadows;
  - determine the relative inaccuracy of fire detection due to sensor properties (*e.g.*, signal to noise ratio) and scene variability;
  - explore the utility of spatial context and multi-temporal approaches; and
  - account for cloud cover in calculating statistics to estimate the occurrence and number of fires.
- Capabilities of geostationary satellites should be improved to permit greater operational use for fire monitoring, by:
  - improving the spatial resolution of thermal channels; and
  - developing consensus algorithms for global coverage (GOES+MSG+MTSAT).

Burn scar products

- Investigate wavelength selection, combinations and transformations appropriate for burn scar detection.
- Investigate the sensitivity of automated burn scar detection to land cover and its properties, the size and shape of burned areas, and confusion with other forms of vegetation removal.
- Investigate the use of SAR for estimating burned areas, especially in areas of persistent cloud cover. Further development is needed to define automated techniques and operational observational requirements for SAR.

New products

- Define specifications for derived fire products (*e.g.*, fuel load, moisture content, fire intensity, fuel consumption) through dialogue with users using avenues of communication provided by GOFC-Fire and DMSG-Fire.
- Develop a means to include fire properties in global fire products, including fuel loads, fire intensity, fire severity, fuel consumption, flaming versus smouldering combustion, fire damage, emission factors, and emissions rates.
- Develop models that will allow users to assess the likely outcomes of different fire policy and management options.

Multi-sensor integration

- Develop multi-sensor algorithms and techniques for fusion of products from different sensors.
- Develop tools for the integration of fire detection (hot-spot) and fire area products.
- Carry out critical inter-comparisons of active fire detection and burn scar mapping products using data from operational and research sensors.

Research and development for historical data

- Compensate for changes in sensor characteristics as new sensors come on line.
- Undertake retrospective demonstration studies using the 15-year record of AVHRR data and regional 1-km archives to develop fire frequency products.

Regional and global approaches

- Develop a consensus on algorithms for global use building on experience gained with existing regional algorithms; begin with AVHRR and move to other coarse resolution sensors.

Validation

- Implement a rigorous fire product validation program with regional and local partners from the producer and user communities.
- Develop:
  - protocols for active fire and burned area product validation;
  - active fire validation metrics with identified sources of independent validation data;
  - data pre-processing and quality assessment procedures optimized for fire products; and
  - fire information reporting protocols.
- Areas of particular concern:
  - validation experiments are needed to determine the accuracy of fire detection and burn mapping using different sensors and algorithms;
  - cost-effective and statistically adequate sampling schemes are needed to determine burned areas using Landsat and other high resolution sensors; and
  - accuracy of sub-pixel estimates for both fire area and fire detection need to be developed for coarse resolution sensors.
- Establish a global network of active fire and burned area validation sites representing a range of spatial and temporal characteristics of burning.

Demonstration projects

- Initiate regional burned area mapping projects with ATSR and SPOT-VGT and MODIS, leading to the generation of a 1-km resolution global area burned product, producing annual products initially, and more frequent products in the future.
- Make use of the JRC WFW network to obtain feedback on utility and shortcomings of global fire products. Evaluate the suitability of a web-browser interface, such as the JRC-Global Environmental Information System.
- Develop a demonstration project, integrating data from geostationary and polar-orbiting satellites, to detect active fires and develop burn scar products for different regions of the world. Eastern Asia, Australia, and Africa are suggested as priority candidate areas.

Continuity

- Move towards self-supporting and continuing regional and global networks by building on existing networks whenever possible.
- Extend fire data records by using a combination of archival data, acquisitions from current sensors, and sensors launched in the near future.

Conclusions

Specialists from 23 nations, representing both information users and data and information providers, have worked to plan the implementation of the Forest Fire Monitoring and Mapping component of Global Observation of Forest Cover (GOFC-Fire), which is now a panel of the Global Terrestrial Observing System. User requirements and current technical capabilities have been reviewed and are reported in this issue. On the basis of these reviews, the specialists held a workshop at the Joint Research Centre of the European Commission in Ispra, Italy, from November 3rd to 5th, 1999, to discuss and draft plans and recommendations.

The primary objectives of GOFC-Fire are to provide leadership in articulating user requirements, and to work with both users and producers to ensure a transition from research projects and proof of concept systems into ongoing operational systems. This will be accomplished by establishing an Implementation Team which will meet annually to track the progress of GOFC-Fire and to formulate new tasks. It will promote a coordinated suite of projects, each of which will be designed to advance a specific GOFC-Fire objective.

Areas in which GOFC-Fire intends to be active include:

- Liaison with users to define and promote the development of new fire products, especially those related to pre-burn fuel loads, post-fire vegetation condition assessment, and carbon emissions.
- Liaison with international organizations, particularly UN/FAO, UNEP, and IGBP.
- Promotion of knowledge of, and access to, fire data and derived products, including:
  - promotion of regional and global networks working toward common objectives by sharing knowledge, experience, data, and information products;
  - documentation of product standards.
- Algorithm validation, and development, and inter-comparison.
- Demonstration projects to ensure widespread dissemination of fire products to users in a timely fashion, and to incrementally develop new capabilities.

The workshop produced numerous detailed recommendations addressing relationships with users, regional networks, documentation and standards, institutional and technical infrastructure, research and development priorities, product validation, and demonstration projects. The GOFC-Fire Implementation Team will follow these recommendations in carrying out its work, and will bring recommendations which are beyond its immediate control to the attention of the relevant organizations.

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