Fire in the Environment

The Ecological, Atmospheric, and Climatic Importance of Vegetation Fires

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Group Report: Quantification of Fire Characteristics from Local to Global Scales

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INTRODUCTION

Interest in biomass burning has been heightened by the recognition of its importance in a wide variety of earth and atmospheric processes. Fire has been a constant companion of humankind in its efforts to satisfy its needs; changes in patterns of resource utilization and technologies have also led to changes in the extent, nature, and severity of the impact of burning. A sizeable body of work on fire has concentrated on individual events and on the characteristics of the burning process itself; there is now a recognized need to produce assessments of the characteristics and effects of fire at hitherto unexplored scales. This calls for a better understanding of burning on regional and global scales, a better appreciation of historical changes that have affected the use of fire during various periods of human history, and, if possible, improved predictive capabilities to chart future trends and possible impacts.

This report is concerned with the study of vegetation fires on various geographical scales and, more specifically, with the feasibility of producing regional and global assessments of emissions associated with the phenomenon. The approach we adopted is threefold: first, we present a review of the body of current knowledge on biomass burning, with particular reference to parameters which could be used for cross-scale analysis, based on the background papers prepared for the workshop; second, we propose a system to integrate the various sources of information and operate a "fire information machine" on regional to global scales; and third, we assess the feasibility

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of incorporating classical fire behavior and emission models into the new approach. The focus of this work has, therefore, been on integration of knowledge and not on experiments.

A series of considerations is necessary before embarking upon this exercise. This Dahlem Workshop has shown, among other things, that the enormous body of knowledge on fire must be organized in a concerted fashion if it is to lead to improvement in our global assessments. Because of the complexity of the topic and the lack of conceptual models, attempts at integration have never been made. This workshop has provided a unique forum to identify the main features of what such a biomass burning information system could be. It has also allowed an evaluation and selection of appropriate technologies for supporting the approach. It has identified conceptual, informational, and technological gaps in the body of instruments currently available for making the assessments. And it has become evident that a framework is now needed to incorporate this often piecemeal knowledge and to stimulate interdisciplinary linkages. In this report, we propose such a framework, admittedly very crude. Through progressive testing and refinement, we believe that it will represent a promising avenue of collective investigation in global environmental monitoring.

An overriding concern of our group involved the complexity of the burning process. Unlike many modeling exercises, where a level of complexity can usually be associated with a level in the hierarchy of nested systems, complexity and variability in biomass burning appear as high on the regional or global level as on the local level. This implies that simplification required at a given level cannot be a substitute for the unmanageable complexity found at a lower level. The statistical implications of such observation are yet to be assessed.

To structure the discussion on the three elements of analysis referred to above (review, design, and integration), we begin with the presentation of a conceptual model of "Vegetation Fire Information System" and a discussion of the various elements of the system as they appear in the construct.

A VEGETATION FIRE INFORMATION SYSTEM: THE CONCEPTUAL DESIGN

The enormous complexity of fire behavior is due to the large range of fuel characteristics and environmental conditions that affects the dynamics of burning. Fire behavior is extremely sensitive to a series of drivers that, depending upon the particular combination of circumstances, may act in one direction or another (increase or decrease in rate of spread, heat output, flame length, and emissions of various products). The level of detail which is required for understanding fire behavior in a single event can, as a rule, not be supplied at the ecosystem or regional level. Furthermore, current fire behavior models are essentially valid for the conditions used in their formulation; generalization of such "episodic" models to larger scales and aggregation of the results under a wide range of conditions still appear impractical.

Thus, current fire behavior models, as such, would not be considered as the building blocks of a global assessment of wildland fires.

The lack of detailed fuel and environmental descriptors demanded by current models makes the development of a new vision imperative. A new generation of models is needed. The ecosystem approach provides an alternative point of entry into the problem. From this perspective, it is the ecosystem characterization, in terms of fuel situation and fire occurence, that drives the selection and activation of the "stylized" interpretative model of fire behavior and fire emissions. This complex operation will lead, on a regular basis, to the production of estimates of the contribution of individual portions of land (i.e., a cell or a pixel) to the gas fluxes associated with burning. The proposed fire information system thus includes the following elements (Fig. 19.1):

- A data base organized into a geographical information system; this data base includes vegetation parameters relevant to the fuel situation in a particular cell (e.g., fuel types: wood vs. grass) and to the burning practices normally associated at the local level.
- A meteorological data base.
- A satellite observation system that can detect a "fire pixel" and trigger the initiation of the fire model.
- A suite of fire behavior and fire emission models on call.
- A fire model that incorporates the various sources of information, produces the required fire-related parameters for a particular spot on Earth, and keeps a record of the particular fire history of that spot.
- A user-driven statistical integrator summarizing the results over space and time according to particular needs (summary reports, statistical updates, etc.).
- A suite of testing procedures that can ultimately be used to validate the model output.

These components are discussed in more detail below.

Several components of the information system proposed here can already draw upon a large body of accumulated experience. Many of them call upon advanced techniques of modeling, geographical information system implementation, and the use of remote sensing. Experts in various fields can therefore assess, with some level of confidence, the contribution of each discipline to the particular tasks included in the overall system. We expect that progress can be made on a short-term basis by organizing such knowledge in the proposed framework. The challenge of the task lies more specifically in the integration of these various data sets and interpretive models into a coherent and realistic operational system, which will yield the desired output. At the current stage of development, we consider the present proposal as a first "testable exercise for reducing uncertainty" in estimating global emissions from vegetation fires and other biomass burning.

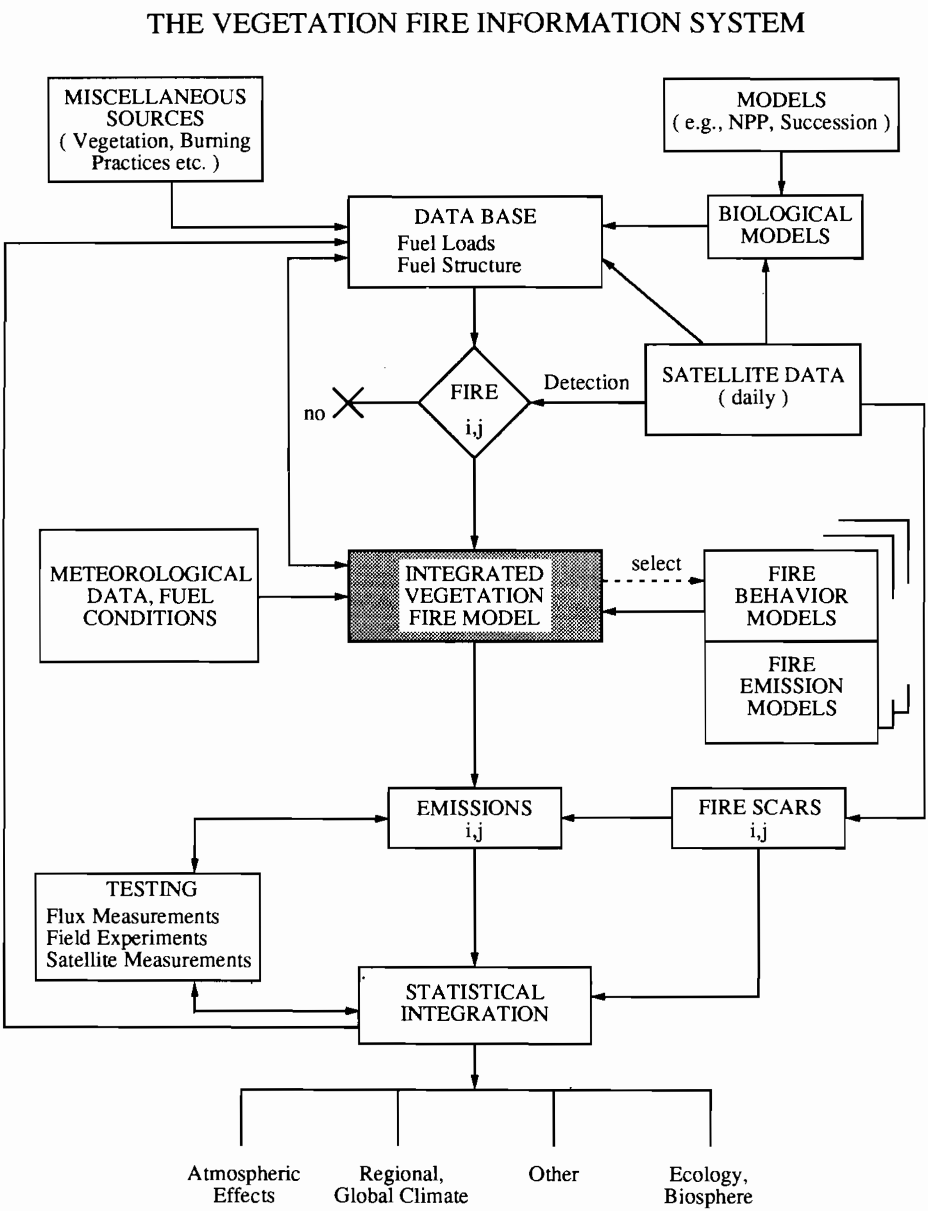

Figure 19.1 The Vegetation Fire Information System: an integrated biomass burning model.

INFORMATION SYSTEM COMPONENTS: A REVIEW OF THE CURRENT STATE OF KNOWLEDGE AND DEVELOPMENT NEEDS

The Spatial Data Base: Vegetation and Meteorology

Vegetation

Geographical information systems provide convenient ways to assemble and organize the data necessary to support the fire information system. As a rule, and given the nature of burning processes in landscapes, these data are elaborations derived from more basic vegetation and terrain data sets.

Spatially referenced information on fuel structure, fuel loading, and burning practices are indispensable.

1. *Fuel structure* relates to the fractional distribution of size class of flammable material. The characteristics of the fuel complex determine the partitioning of the flaming and smoldering combustion phases during a particular episode. Flaming and smoldering combustion are distinctly different processes; they involve different chemical reactions and emissions characteristics. Currently, fuel type maps must be derived from vegetation and/or biomass maps supported by field sampling. However, the relationships between vegetation type and fuel type have not been established for plant communities on a global basis. More research, which may incorporate new types of remote sensing measurements (such as those provided through microwave techniques), is needed to refine current capabilities. Changes in vegetation cover due to human activities, impact of burning, and climatic variations must obviously be updated regularly.
2. *Fuel loading* refers to the time-related distribution of flammable material in vegetation. This factor evolves throughout the season. Two approaches to its evaluation are possible. The first one uses standard tables of seasonal fuel loading in typical vegetation formations; this approach is supported by field measurements and a knowledge of the fire history of the particular site (the absence of fire will accumulate flammable material at a given rate). Estimations of the combustion process will be greatly improved if fuel loading is calculated per category, as identified in the vegetation structure analysis referred to above. A more dynamic approach is to use biomass models that, throughout the plant life cycle, will predict (a) the amount of photosynthetic material produced during a particular growing season and (b) its partitioning into green/nongreen material during senescence or as the dry season evolves. Various models already exist and their outputs can be used regularly to update the data base. Remote sensing is a possible source of information on vegetation conditions since it can supply relevant data on biomass accumulation and phenology which, in turn, can be interpreted in terms of fuel loading. This approach is currently feasible for grass savanna but is of less value for mixed woodland or forest ecosystems.

As a whole, it is clear that the characterization of fuel needs to be refined and that its analysis must now be performed in a wider variety of ecosystems (see list in the section on **Fire Models**).

3. Information on *burning practices* is required since, to some extent, human practices purposefully control fire characteristics. Therefore, for our purposes, this dictates the selection of a particular fire behavior model. Practices normally adopted in a given area are often the main determinant of the type of fuel and combustion processes being involved in the burning. Quick fires used for hunting are different than agricultural clearing fires; undergrowth clearing is done under different conditions than the burning of woody debris in piles. Again, a general knowledge of such practices must be brought into the data base to help in the stratification of the fire landscape. This general knowledge may, however, suffer from the fact that practices can be adjusted on a short time scale in response to new environmental or technological conditions; remote sensing of spatial patterns of burning may provide additional and more updated information in such respect.

The GIS approach gives a unique opportunity to prepare the necessary data bases in a flexible manner. It can accomodate data produced at different scales and manipulate them at different levels of aggregation. It can, in addition, provide a structured repository for field data.

Meteorology

Local weather conditions determine the moisture content and flammability of the material and govern fire spread. Given their overriding impact on the variability of fire characteristics, it is mandatory that such information be available at the time of the fire event itself. Windfield at the surface, air moisture, and rainfall during the preceding period are the three parameters of interest in determining moisture content and fire behavior (rate of spread). In the proposed system, such local variables are to be extracted from the data sets if and when there is an active fire in the cell of observation. It is likely, however, that only regional parameters will be available and that the temporal frequency at which they are acquired will not match the requirements for information during a precise period of the diurnal fire cycle. The overriding issue in linking with meteorological variables is that, in some circumstances, a driver such as wind operates at a microscale and predominates all other measurements at any other scale. Scale inconsistencies may thus appear. Until improvements are made in the meteorological data bases, statistical correlations between regional parameters and moisture content of vegetation have to be used. For instance, information related to water balance could at some stage be derived from hydrologic models under development.

Fire Event Detection

The detection of a fire event is the operation that initiates the fire model. In the absence of this event, for the particular cell under consideration, the system remains on standby while still actively monitoring vegetation (fuel loading) and meteorological conditions.

Once a fire has been detected in cell i,j, the process of interpreting the available background and time-related information for that pixel is initiated. A decision could then be made to apply simple probabilistic models of combustion and emission based upon empirical data. Alternatively, a fire behavior and fire emission model can be selected and activated. This point will be covered in more detail below.

The only practical and feasible way of keeping a permanent watch on regional and global biomass burning events is through remote sensing. Research has shown that the AVHRR (Advance Very High Resolution Radiometer) instrument carried on the NOAA (National Oceanographic and Atmospheric Administration) series of satellites can be used to detect elevated heat sources, especially in the 3-micron range. Fire detection is therefore possible in some specific circumstances. The 1-km resolution of the instrument has the advantage of providing daily views of the Earth's surface, and this yields data rates and data loads that are manageable for regional monitoring. The data are cheap and can be collected economically on a regular basis. The usefulness of the AVHRR approach for fire accounting has been well demonstrated in many tropical areas, such as the Amazon, Borneo, and West Africa.

There are, however, limitations associated with the type of sampling performed by the AVHRR instrument. First, the satellite orbit provides only a single daily afternoon (the night pass is often not recorded), which is only a small window in the daily burning cycle; it is important here to assess the representativity of this temporal sampling for each type of burning region. Adjustments can then be made to account for the bias. Second, a limitation of the instrument is that it saturates at a relatively low temperature, which means that fire events will not be detected if the background has already reached such a threshold temperature (320 K). Third, the resolution of the sensor is such that it can only detect the presence of "fire" in the pixel; the number and size of fires that may be present in that pixel cannot easily be ascertained. Finally, clouds and excessive smoke cover will prevent the observation of the Earth's surface in the spectral range used by the AVHRR. In summary, current technology allows a systematic scan of the Earth's surface on a daily basis and the detection of the presence/absence of a fire event in a pixel. This can be done in a consistent fashion over large regions. "Invisible," undergrowth, or very small-scale fires are unaccounted for by this AVHRR approach; their occurrence and frequency must be taken into account in the data base. At present, under the IGBP–DIS (International Geosphere Biosphere Program–Data and Information System) auspices, efforts are being made to standardize the processing of the AVHRR data, to normalize the interpretation of fire detection, and to maximize the extraction of global information. The feasibility of assembling and analyzing global

1-km AVHRR data sets for fire monitoring is also examined under the Global 1-km Coverage Project.

The biomass burning information system will obtain the daily AVHRR data for the area concerned and conduct a per pixel identification of the occurence of fire. When possible, algorithms will be applied to determine the fire fraction in the pixel and its brightness temperature. The accuracy of such an estimate is dependent upon being able to determine a background temperature at a local scale. Temperature thresholding between flaming and smoldering phases should then be possible. A decision rule will trigger the continuation of the analysis in case of positive detection and channel the relevant fire characteristics to the biomass burning model. Future remote sensing instruments specifically designed to detect and measure fire characteristics are discussed in the concluding section.

It should be noted that if current remote sensing capabilities are most often considered with respect to vegetation conditions and fire event identification, techniques can also be used for measuring smoke and aerosol characteristics and thus characterizing emission products. The analysis of single scattering albedo of smoke plumes is examined below (see section on Testing of Results). The issue of fire temperature as a discriminant of flaming/smoldering phases is left open.

The Vegetation Fire Information System model could provide the framework for estimating changes in burning patterns and emissions in modern history and for predicting fire emissions in the future. Indeed, information on fire events currently proposed as derived from satellite data could be substituted by historical land-use change data for anthropogenic fires and by probability distributions of lightning fires (the size of the cell would then have to be adjusted accordingly). This effort should be done in cooperation with historians, social scientists, and anthropologists. Future predictions of the contribution of vegetation burning to atmospheric chemistry could also use the same model presented in Fig. 19.1. In this case, scenarios of increased population and potential climate change would be introduced to adjust the incidence of fire regimes.

Fire Models

Once a fire has been detected in a given pixel, the analysis of its characteristics is triggered. This calls for the selection and activation of a fire behavior model, which then feeds a fire emission model. The characteristics of these models are important to consider because they determine data requirements and modes of operation.

The overriding importance of distinguishing between flaming and smoldering combustion is emphasized in fire emission studies. They are two distinctly different processes that involve different temperatures and chemical reactions. Flaming dominates during start-up, with the fine material supplying the volatile fuel required for the rapid oxidation reactions to be sustained (combustion efficiency ranges from 0.85 to 0.95). Once the fine fuels have been consumed, the flaming combustion subsides and dies because the heat feedback to the more compact and/or the large diameter fuels can no longer sustain the rate of volatilization required to maintain a flammable mixture of fuel gases. With the onset of smoldering combustion, the efficiency decreases (0.65–0.85). The rate of smoldering combustion decreases following an exponential decay curve with a factor depending upon the moisture content and other properties of the fuel bed. Smoldering can range from negligible for some grassland types to extensive in deforestation fires. Because of the large differences between the two phases, it is essential to characterize emissions independently for each phase and calculate the weighted averages for the fire. For some fuel types, emission factors for carbon species correlate well with combustion efficiencies (ratios CO/CO_2, $CO_2/[CO + CO_2]$, etc.). To the extent that flaming and smoldering combustion efficiencies can be estimated on the basis of moisture content, distribution of size classes of fuels, and fuel bed properties, emission estimates can then be made. These models have to be parameterized in a wider set of conditions than the ones they have been developed for. We suggest that a series of stylized fuel-type models be developed for the following ecosystems, which represent the largest areas of biomass burning:

1. Grassland–Savanna
   grassland (short grass as in cerrado, steppe)
   mixed savanna woodland
   dry savanna open woodland
   moist savanna
   pastures (e.g., Amazon ranches)
2. Tropical Humid Forest
   mature (primary) forest: cleared, uncleared
   secondary forest (various stages of succession): cleared, uncleared
   forest in shifting cultivation cycle
3. Seasonal Forest
   mature (land fire climax): cleared, uncleared
   secondary (mid to late stage): cleared, uncleared
   degraded forest fallows (e.g., in shifting cultivation cycle)
4. Agriculture (intensive, extensive)

These models will include fuel-type description and have features that provide for the calculation of relative spread, consumption, and combustion efficiencies under a series of weather conditions.

While it appears that the importance of biomass burning emissions dictates that priorities be given to measurements, process models are still needed for refining the estimates of carbon emissions and for dealing with sulfur and nitrogen species. Information on the elemental composition of the fuels by size class is again necessary as oxidized species are released more abundantly during the flaming phase and reduced species during the smoldering phase of combustion.

The relative importance of some gas species in global processes has to be considered when establishing priorities for research. The identification of chemical tracers associated with biomass burning can help in partitioning the role of various combustion processes in the changing characteristics of the atmosphere. Carbon monoxide, CH_3CN, HCN, and aromatic compounds such as pyrene and potassium on particles are good candidates for such analysis.

The importance of nitrous oxide (N_2O) as a key atmospheric gas is also underlined because it has significant radiative and chemical properties which give it a greenhouse warming potential of more than 200 CO_2 molecules. For the most part, it is chemically active in the stratosphere, where it is destroyed by photolysis and by the reaction with excited atomic oxygen, which leads to the production of nitric oxide. This reaction is responsible for about 70% of the catalytic chemical destruction of the stratospheric ozone.

Regional and global analyses of vegetation fires are essential for determining the effects of fire on the global geochemistry of nitrogen, phosphorus, sulfur, potassium, and other elements. Recent measurements show, indeed, that fire converts substantial quantitites of fuel nitrogen to N_2, thereby representing a significant net loss of nitrogen from terrestrial ecosystems. Smaller fractions of phosphorus are mobilized in aerosols; however, they could have substantial effects on recipient ecosystems.

Apart from direct vegetation fire emissions, it is important to consider the post-fire effects linked to soil processes. Nutrient cycling, including nitrogen fixation and translocation in fire ecosystems, is an important topic in ecology. Burning may also stimulate or reduce biogenic emissions of N_2O, depending on the time scales involved, and contribute significantly to its global source. Other aspects of post-fire analysis are treated below.

We would also like to mention the global emission inventory activity (GEIA) of the IGAC (International Global Atmospheric Chemistry) as being a possible reference source in the global emission inventory relative to the various gas-producing processes including biomass burning. The data set for the monthly inventories with eventually 1 × 1 degree cells will soon be available on diskette to interested investigators.

The Vegetation Fire Model

The integration of fire behavior and emission model outputs with the information derived from the data bases are done in the central fire model. This "gray" box in the flowchart (Fig. 19.1) must be considered as the central processor, where data and information are requested and parsed according to the conditions in the cell and the needs of a particular model. It should also be a decision platform where the outputs of the fire models are evaluated, rejected, or accepted. The continuous improvement of calculations and decision rules must be built into the system through a series of iterations and progressive adjustments. The challenge here is to design a system which can, statistically or otherwise, learn to optimize the use of the available data and thus maximize the accuracy of the results. The fire model should also be amenable to sensitivity analysis which, among others, could be designed to identify the major source of errors. This information would help to establish priorities, in terms of research and development.

The problem involving the scale of observation of fire and burning processes was of particular relevance to the perspective adopted by our group. The information system proposed here is essentially based upon a point-by-point analysis; yet it is clear that if regional and continental assessments of fire in vegetation are to be produced, enhanced attention will have to be given to regional patterns. These patterns—revealed, probably for the first time, by remote sensing data—can be considered as higher units in the hierarchy of events related to burning. In such a framework, the individual fire used as a unit of analysis in fire behavior/emission models may give way to approaches based on a stratification of fire landscapes. This new type of analysis will have to be integrated in the proposed system.

Testing of Results (Validation)

While it is premature to consider model validation in a strict sense, various possibilities exist to test the soundness of the results or corroborate them through convergence of evidence. They range from field experiments to regional flux measurements by aircraft and satellites.

Large-scale field experiments, such as those ongoing in the SAFARI project (Southern Africa Fire–Atmosphere Research Initiative), are essential to address the problem of source characterization, modeling of emission, remote sensing application, and regional flux measurements in somewhat controlled conditions. Such field experiments should be designed to enhance systematically the knowledge and experience with respect to the components of the overall information system described in this report. It is therefore desirable that a series of experiments be launched to address specifically these questions on a regional scale. It is furthermore important that they progressively cover a wide variety of ecosystem and atmospheric conditions.

Flux measurements are prime candidates for calibration experiments. They give us the opportunity to address measurements at regional scale as a means of calibrating the emissions from a given fire complex (as opposed to individual fires). They are designed for verifying the prediction of the source term. Limitations are related to the effects of transformations (e.g., removal mechanisms), which lie between the source and the transects used for flux measurements. The strong dependence of measurements on meteorological conditions is another source of error. The range of possibilities for collecting flux measurements is large and may include measurements from single plume to regional, at varying altitudes, and at different distances from the sources. The use of satellite data for measuring plume and smoke characteristics has been mentioned elsewhere in this volume (see Justice et al., this volume).

Statistical Integration of the Results

The aggregation of the model results, obtained on the basis of a single cell over a large area and for selected periods of time, is guided by individual requirements. Indeed, one can imagine a variety of needs that could be satisfied if such flexibility were built in the output presentation. The questions and needs related to the model must obviously consider the still limited resolution of the input data. While the system presented here has been oriented toward regional and global emission estimates, other outputs can possibly be derived, such as those of interest in climate studies (aerosols), in ecological studies (heat fluxes, patchiness, degradation, recovery process) or large-scale fire management projects (early warning, monitoring, etc). However, it is recommended that the exercise starts with relatively well-identified objectives and progressively adds more complex issues.

ASSOCIATED ISSUES

Complex information systems, such as the one outlined in our report, must be tested and adjusted through the course of dedicated experiments used to mimic real world situations. As a rule, they cannot be sustained as truly operational systems without a long-term support needed for a continuous supply of the necessary inputs. These input data are derived from research results (i.e., model development), technological advances in data management, and remote sensing systems as well as from continuous links with data sources such as global observation systems and meteorological data streams. Many of these require institutional support of a different kind than those associated with research and development.

Fire scar analysis, which is highly amenable to remote sensing approaches, has yet to be fully examined. The inclusion of such analysis in the information system described here is not straightforward. Indeed, scar analysis is usually performed at some time after the fire events and therefore cannot be included in a "running" emission model, which is activated at the time of the appearance of a fire pixel. An alternative is to include this area component at a later stage in the analysis and testing. The final estimates would, in such cases, not be completed until a regional fire scar analysis has been conducted. One can also consider including fire scar analysis as a verification of the fire behavior output in terms of area and fuel consumption efficiency. This supposes, among other things, that a relationship be established between the radiometric characteristics of the burn and the thoroughness (severity) of burn or fuel consumption efficiency. Fire scar analysis may, in addition, provide historical evidence of fire periodicity.

It must be noted that fire scar analysis is also very relevant for assessing the contribution of post-fire emisssions to the source (N_2O, NH_3, and other possible trace gases). The spatial data related to the distribution of scars (e.g., fragmentation) as well as their post-fire evolution includes information of interest in the ecology of recovery.

A recognized and serious weakness of the approach proposed here is the lack of information on injection height and plume development associated with individual fire episodes. Remote sensing could have a role to play in providing measurements of plume skin temperature and thus height.

The problem of resolution is still entirely undefined. As seen, the current choice of resolution has been driven here more by technology than by reason. The AVHRR remote sensing instrument has a nominal resolution of 1 km, and this is taken as the size of the working cell. It is obvious, on one hand, that there are many data bases which do not provide such resolution and that, on the other, the variability of fire characteristics can be extremely large in a 1-km square area. Technically, the 1-km resolution may lead to volumes of data that, in terms of handling, will present serious challenges.

In our current proposal, the question of the time step adopted in the running of the model is also left fairly open. The daily frequency of satellite observation will again impose serious constraints on the operations. Weekly syntheses of fire situations may be designed and meteorological data may be available daily; however, fire behavior is sensitive to fuel moisture content that can change hourly. As hourly computations are impractical, a "canonical" or typical diurnal variation of moisture content by season may be modeled. Such an approach must be further developed.

A successful implementation of the above-described information system would provide a solid framework for better quantification of issues of global change related to biomass burning. Most obviously, a better description of current sources of aerosols and atmospheric trace gases plus estimates of past history, will provide inputs to models of climate and atmospheric chemistry change. Conversely, the proposed information system, by organizing present knowledge related to fire frequency and environmental conditions will provide the framework needed for relating fires to future climate change.

PROSPECTS

This Dahlem Workshop on "Fire in the Environment" has largely focused on a set of scientific issues related to the study of vegetation fires. The challenge faced in expanding our current knowledge of combustion processes to regional and global scales is formidable. We have proposed a framework that, while still lacking the desired operational characteristics, can help organize collective knowledge, identify priorities, and chart future courses of action. In addition, we also propose that a multidisciplinary group of scientists examines, in more detail, the feasiblity of such an undertaking and begins to identify concrete steps to be taken to move forward. This international scientific effort could be organized under the IGBP umbrella, by calling upon interested scientists in the four core projects currently involved in activities related to biomass burning; these are the IGAC core project, the GCTE (Global Change in Terrestrial Ecosystems) project, the GAIM (Global Analysis, Interpretation and Modeling) project, and the IGBP DIS pilot project.

RECOMMENDATIONS

An interdisciplinary project should be set up leading to the development of a global biomass burning information system. Given the multidisciplinary nature of such projects, an IGBP umbrella is recommended for its implementation.

Such a project should be strongly supported by a series of coordinated field experiments, including campaigns in a variety of ecosystems. The IGAC–BIBEX–STARE approach should be continued and applied to other critical parts of the world.

Field studies on biogenic soil gas fluxes after fire should be undertaken to understand better the contribution of post-fire emissions and nutrient turnover in soils to global chemistry and global climate.

Research should focus on quantitative estimates of changes in burning patterns and associated emissions for key epochs in modern history: 1500 as the end of pre-Columbian period, 1850 as the beginnning of industrial period, and 1990 as the present benchmark. Attempts should also be made to predict the future of biomass burning contribution to global chemistry towards the year 2050.

An integrated study of the effects of fire on the regional and global cycles of nitrogen should be undertaken. This should include assessments of the conversion of biomass nitrogen in N_2 and of the effect of interbiome translocation on the nitrogen budget.

Efforts should also further focus on the development of fire models, which together with experiments can lead to prediction of emission characteristics.

Spaceborne sensors specifically designed to detect fire events and related parameters are needed if progress is to be made in the global monitoring of vegetation fires. Currently, space agencies have not considered the issue. It is therefore recommended that the science community ensures the priority development and launch of appropriate instrumentation by the appropriate agencies. This includes thermal sensors in the temperature range associated with burning as well as improved instruments for global vegetation monitoring.

The global satellite data set derived at 1-km resolution from the NOAA–AVHRR instrument can provide the material for a prototype global fire product, which can be used in the framework of the fire information system proposed in this report. An analysis of that data set relevant to vegetation and fire should be undertaken under the coordination of the IGBP–DIS project.

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