Modeling the Effect of Land-Use Changes on Global Biomass Emissions

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ABSTRACT

The rate and magnitude of emissions from prescribed burns and wildfires in wildland areas throughout the world are related to biomass consumption, which is controlled by total biomass, fuel moisture, fuel distribution (fuel size and arrangement), and ignition pattern. Consequently, land-use practices, which can affect many of these components, play a crucial role in determining the rate and magnitude of smoke production from biomass burning. The variability of land-use and its relation to the magnitude and rate of smoke production, however, usually are not

considered when estimating biomass emissions. For example, much prescribed wildland burning in the United States has changed from high-intensity slash burning associated with land clearing activities, in which 20 hectare fires typically emit more than 10,000 grams/second of particles within an hour or two, to low-intensity understory burning related to health management where 120 hectare fires emit less than 2,000 grams/second of particles for several hours to days. Total emissions may be similar but the duration of emissions and associated heat release rates are significantly different, causing vastly different impacts on visibility, human health, and climatic forcing. Despite changes in land-use and fire, many regional and global estimates of biomass emissions in the United States continue to assume that most emissions result from land-clearing type slash burns. Meanwhile, in South America estimates of biomass emissions typically assume dry fuels, yet most burning occurs within a few months of harvesting. The large logs remain wet, reducing emissions by more than 50%, which is unaccounted for in global emission estimates. Also, while land-clearing remains vigorous in the tropics, a change toward using fire for health management already has begun.

In this paper, an emission production model is used to show the differences in emission magnitudes and rates for prescribed fires in rain forests of Washington State and the Brazilian Amazon, and in dry forests of Oregon State and the Brazilian cerrado. In addition to emissions of particles and carbon gases, the model estimates heat release rates that affect plume buoyancy. These values are used to evaluate impacts on human health, visibility, and components of climate forcing.

INTRODUCTION

Biomass fires are a significant cause of regional air pollution and an important global source of carbon to the atmosphere. Because the magnitude of emissions from biomass fires is so large, many attempts have been made to assess their effects on the global carbon budget. Efforts are underway to reduce emissions that contribute to climate change and affect health and welfare. The effectiveness of these efforts can be evaluated by assessing their influence on the number and size of fires that occur, the consumption of biomass by those fires, and emission characteristics. An Emission Production Model, EPM, is used here as a way to refine large-scale estimates of fire emissions, track incremental changes in emissions over time, and to evaluate the effect of land-use and fire-management practices.

Emissions from biomass burning contribute roughly 6% of the particulate emissions from all global sources (Andreae 1991), but the regional contribution to the global budget is changing with time due to changing land-use practices. There has been significant recent emphasis on tropical areas because the rate of tropical deforestation clearly dominates current global emissions from fires (Laursen and Radke 1996). During the agricultural revolution in the late 19th century, however, northern latitude emissions were globally significant (Holdsworth et al. 1996). Also, recent experiments suggest that current emissions from North American and boreal fires may be much greater than some recent estimates (Hegg et al. 1990; Cofer et al. 1996). Predicting future emissions from fires will depend significantly on how well changes in land use and climate are predicted, how well we model the effects those changes have on emissions, and how consistently we are able to model changes across the world's biomes.

Changes in climate and land use are incremental, so the methods we use to assess the impact of change must be dynamic enough to capture transient responses. Global estimates of fire emissions, however, typically are based on static models that make simple calculations about biomass consumption, and assume an average pre-burn loading and constant fraction of consumption in each biome. Seasonality, climate variability, and differing burning characteristics often are simplified or ignored. Diurnal timing and buoyancy are not generally considered.

The Emission Production Model (EPM: Sandberg and Peterson 1984) can address much of the variability currently lacking in global biomass emission estimates. It was initially designed over a decade ago to estimate emissions and heat-release rates from individual prescribed fires, so that management options to reduce emissions and their local impact on air quality could be evaluated. Development since then has incorporated more robust algorithms that address a wide range of burning styles, vegetation types, and fuel conditions (Sandberg and Ferguson, in preparation). Use of the model is expanding from its initial local application to having greater utility in assessing large-scale regional and global emissions as well as other fire effects.

CHARACTERISTICS of FIRES

Wildland fires are increasing in many parts of the world due to increased human pressure and an apparent increase in the severity of climatic conditions leading to large catastrophic fires. Although attribution is difficult, the observed warming of the planet during the past two decades has been coincident with an increase in fires in ecosystems ranging from the tropics to the boreal forests during the last two decades (e.g., Agee 1993; Prins and Menzel 1994; Larsen 1996). Partly as a result of these natural disasters, policy makers and scientists are gaining appreciation for the values at risk from fire as well as the ecological importance of fire. The use of prescribed fire to sustain ecosystems, prevent catastrophes, and manage natural resources is on the increase in many countries of the world. Also, of course, the use of fire to clear forests for conversion to agriculture, especially in the tropics, continues at an alarming rate.

We use the term "fires" to be inclusive of "prescribed biomass fires" (i.e., those that are intentionally used to accomplish resource and land-use management objectives) and "wildland fires" (i.e., all fires that are unintentional). The term "wildland fuelbeds" excludes agricultural fuelbeds, but includes all of the live and dead biomass between the mineral soil and the top of the dominant vegetation canopy of ecosytems. Fires vary widely in their intensity (heat release per unit time) and severity (heat release per unit area) because of differences in the physical characteristics of wildland fuelbeds, the condition of the fuel elements (especially fuel moisture), the current weather, and the nature of ignition.

Fire intensity, which in part controls combustion efficiency and plume rise, varies over several orders of magnitude according to natural and managed variability in fuel condition, weather conditions, and ignition pattern. At one end of the spectrum are prescribed fires used for land-use conversion or wildfires during periods of optimum conditions, with heat release rates sufficient to loft plumes high into the troposphere. At the other end of the spectrum are smoldering ground fires or fires in very light fuels, with heat release rates so low that plumes rarely exceed surface boundary layer heights. Intensity is likely to vary dramatically with diurnal winds and humidity if fires burn more than several hours. Freely spreading fires also vary in intensity from minute-to-minute as wind and other burn conditions change.

Differences in fire severity cause ranges in fuel consumption from about 1,000 to 500,000 kg per hectare. Fires used for land clearing in converting forests to agriculture, grazing, or urban development are intentionally high intensity and high severity with as much as 70% to 90% fuel consumption. The highest consumption rates occur in dry fuels that are densely distributed or piled then ignited almost instantaneously. If burned early in a dry season and soon after logging, however, less than 25% of the fuels may be consumed because high fuel moistures reduce combustion. Fires in the understory of forests or woodlands may consume less than 10% of accumulated biomass as fuels are sparsely scattered and ignition is gradual or spotty. In the same biome, however, if fires involve the dominant vegetation of connected canopies, as much as 60% of total aboveground biomass may be consumed. Fire severity can be controlled by mechanically manipulating the fuel bed, and/or scheduling intentional fires and controlling the ignition pattern.

Other policy options that can limit biomass consumption include preventing wildfires and prohibiting prescribed fires when high severity is expected.

Fire duration, typically ranging from an hour to several weeks, is another important variable. Emissions and biomass consumption can be minimized by nearly instantaneous ignition, creating a short-duration convection column that collapses soon after flaming stops, followed by very little smoldering. Fires that last for many days promote smoldering combustion, higher emission factors (i.e., mass of emissions per mass of biomass consumed), and serve as an ignition source for wildfires. Generally speaking, management practices that promote fires of shorter duration are favored for reducing emissions and for limiting the impact of non-buoyant plumes.

Despite the desire to reduce emissions by reducing fire duration, long-duration fires are becoming increasingly common as land managers promote low intensity, meandering fires that remove fine fuels but do not damage large trees. This is causing the diurnal cycle to play an increasingly significant role in emission rates and related impacts. During the night, emission rates usually decrease. At the same time, however, threats to human health increase. During the day, when emission rates usually increase, greater dispersion allows lower surface concentrations but contributions to regional haze and its impact on visibility and radiative flux become pronounced. Figure 1 shows the light-scattering coefficient, which is proportional to particle mass, from a nephelometer that was placed approximately 4km down-valley from a 360 hectare, prescribed under-story burn in northeastern Oregon. Ignition began at 1100 Pacific Daylight Time (PDT) on 13 May 1997 and flaming was complete by approximately 1600 PDT the same day. Smoke entered the valley from the smoldering fire as soon as radiative cooling at night diminished lofting. Emissions continued for several days, barely noticeable during the day when emissions were lofted away from the valley, but each night smoke settled into the valley as smoldering from rotten logs and old stumps continued. Total particulate emissions from this fire were estimated to be nearly 20 x 10^6 kg. Less than one half of this total was emitted during the first few hours of ignition when heat release rates were relatively high and buoyant emissions were dispersed widely by upper-level winds. The remaining smoke, with over 10 x 10^6 kg of particulate matter, was emitted in the next several days after ignition while the fuel smoldered independently. The weakly buoyant emissions lingered close to the ground surface where they were transported by topographically controlled thermal winds. An estimate of impact based on total emissions would have missed the diurnal variability in emission rates and concentrations.

MODELING EMISSIONS

The Emission Production Model (EPM) provides a time-sequence of heat release rate, biomass consumption, and emission production from any fires in wildland fuelbeds (Sandberg and Peterson 1984). The principal purpose of EPM is to anticipate and manage air quality problems and it is a principle source-strength estimator for a number of smoke dispersion models (Ferguson and Hardy 1994, Breyfogle and Ferguson 1996). EPM has been in widespread use for planning and screening prescribed fires in the United States for fifteen years. The model development is ongoing as science progresses in fuel consumption and heat flux, and as new databases are generated that describe the spatial distribution of biophysical parameters, including vegetation type, fuel characteristics, and ambient weather or climate. Details of the model physics are explained by Sandberg and Ferguson (in preparation). The following describe primary features of the model.

The inputs to EPM are a description of the fuelbed, the rate of fire ignition, and the amount of biomass consumed. EPM is designed to link with a biomass consumption model[1] that provides model estimates of fuel consumption in each combustion stage (flaming and smoldering) for duff, rotten logs and stumps, shrubs, grasses, leafy and needle canopies, and several size classes of sound-dead woody material. Typically, the user inputs ignition intervals for prescribed burns and ignition rates are estimated from the source of ignition (e.g., helicopter dropped incendiaries, hand-held torch, etc.). EPM is being linked with a fire behavior model (FARSITE: Finney 1995), however, so ignition rates can be automatically calculated from the fire spread. This is especially useful for ignition rates in wildfires. For regional and global applications, ignition rates are estimated from the dominant land-use activity. For example, piles usually are ignited within a few minutes, dispersed harvest residue requires several minutes to about an hour for ignition, while the ignition of understory burns usually continues for several hours. In all applications, ignition rates are assumed to be constant during the ignition period.

[1] Currently algorithms from CONSUME (Ottmar et al. 1993) and SMS_INFO (Ottmar 1992) are embedded into the EPM code. Modifications are being made, however, to remove these internal algorithms and replace them with a link to CONSUME v2.0 (in preparation) or other fuel consumption models.

EPM calculates the length of each combustion stage at a point directly from the characteristic dimension of fuel reduction obtained from CONSUME or its substitute. For example, based on laboratory experiments of Anderson (1969) EPM presumes that the flaming stage lasts slightly over 3 minutes for each centimeter of woody-fuel diameter reduction. Once a fuel ceases flaming, the duration of its initial smoldering stage is characterized by an exponential-decay constant, which is derived empirically from the estimates of mass consumed and their characteristic dimensions of reduction (e.g., diameter reduction of wood and height reduction of duff). For example, field experiments have shown that the smoldering rate in short-needled conifer duff (partially decomposed litter) diminishes by a factor of (1-1/e) every 6 minutes for each centimeter of duff consumed. Other fuelbed components can control the rate of initial smoldering as well, so a set of heuristics is included in EPM to choose the optimum method of estimating the exponential decay constant in each fuelbed type.

In addition to a dependent smoldering stage, which is related to the die-back of flaming combustion, there also is an independent smoldering process that occurs in porous fuels like rotten wood, litter, duff (fermentation and humus layers), peat (organic soils), and moss. Independent smoldering rates diminish as a negative exponential, similar to dependent smoldering but with time constants of hours to days instead of minutes. The rate of independent smoldering consumption is related to moisture content, porosity, and inorganic content. Currently a simple kinetic approximation is used with empirical time constants that are based on only a few observations, but research is underway to sharpen this estimate.

The rate of biomass consumption in each combustion stage is calculated within EPM based on fuel description, ignition pattern, duration of each combustion stage, and the exponential time constants. Emission rates and heat fluxes are calculated every 3 minutes by assuming that the flaming and smoldering stages of combustion are at their peak intensity as soon as the fuelbed becomes fully involved in that combustion stage. This assumption has been verified in numerous field studies, and allows the independent calculation of a rate at any time.

An emission factor is derived from lookup tables (U.S. Environmental Protection Agency 1991) according to fuel type, and mass-weighted at each time step according to the ratio of smoldering-to-flaming consumption. The emission factor multiplied by the rate of biomass consumption yields the total emission rate for each pollutant, including several carbon compounds (carbon monoxide [CO], carbon dioxide [CO_2], and methane [CH_4]), particulate size classes (particles less than 10 micrometers in diameter [PM10] and less than 2.5 micrometers in diameter [PM2.5]), and heat release rates (BTU). The model is being updated to include output of large particles and gases that affect regional haze and ozone production, such as sulfur and nitrogen oxides.

The current version of EPM assumes that all of the generated heat is transferred to vertical flux and entrained into a single convective column. It has long been known, however, only 40-80% of the heat is convected, the rest is radiated away from glowing embers and flames or conducted to the ground (e.g., McCarter and Broido 1965). Also, Byram and Nelson (1974) speculate that the convective pattern breaks into separate cells when burning rates are slow relative to the area of burn. Although the assumptions in EPM should overestimate plume rise, tests with a simple dispersion model indicate that modeled plume rise is nearly equal or slightly lower than observed over relatively intense slash burns in the northwestern United States (Hardy et al. 1993). Clearly, more work on this aspect of the model is needed.

The diagram in Figure 2 summarizes the data and computational flow of EPM. Inputs of fuel characteristics are measured fuel volumes or estimated loadings from photo inventories or tables of fuel characteristic classes. Fuel moisture also can be measured immediately preceding a fire or estimated from fire weather or climate indices. These components provide input to fuel consumption algorithms. Currently, the only type of consumption model that distinguishes between combustion phases is CONSUME (Ottmar et al. 1993) but links to future models and other algorithms is possible. EPM then uses the ignition pattern and theoretical equations of combustion processes to calculate rates of combustion from the mass of each fuel element consumed during flaming and smoldering. The ignition pattern is user defined, provided by fire spread models (e.g., FARSITE), or estimated from land-use patterns. Emission factors from a variety of published sources (e.g., Ward et al. 1989) are used to determine emission rates for each pollutant.

Figure 3 shows the characteristics of a typical biomass burn measured over a 8.5 hectare fire (Ferguson and Hardy 1994). Shortly after ignition a flaming phase continues for several minutes during which time maximum release rates of heat, particles, and gases occur. After flaming, sound woody material begins smoldering with smoldering emissions decreasing exponentially.[2] In places with deep layers of duff or rotten wood, an independent smoldering phase can continue for several hours to days. This sequence occurs in all types of fires, from stand-replacement and forest clearing to slash reduction and ecosystem restoration. The magnitude of fuel consumption, and consequently emissions, depends on fuel loading, fuel condition, and ignition rate. The duration of each phase primarily is a function of the size distribution of fuels and fuel moisture.

In addition to measured values of fuel consumption, Figure 3 shows modeled emission rates from EPM. The magnitude and duration of flaming and initial smoldering phases are successfully captured by the model. Because rotten wood was not inventoried in this case, EPM did not predict an independent smoldering phase.

EFFECTS OF LAND USE

To show how differences in land-use may affect biomass emissions, several test cases were derived for EPM. The cases consider typical fuel loading, fuel condition, and ambient weather in broadcast slash, stand replacement, and understory burns. Fuel loading data were selected from measurements in Amazonian primary tropical forest (Kauffman et al. 1994), western Washington Douglas fir rain forest (Hobbs et al. 1996), eastern Oregon ponderosa pine (Ottmar et al., in

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[2] A sharp rise in emission rate seen at about hour 1900 is thought to be due to a practice of lowering the sample packages over the smoldering fire as soon as flaming ceases. Other variability is due to ambient wind and the complex fuel array.

press), and cerrado sensu stricta-denso near Brasilia (Kauffman et al. 1994), a savanna forest. It should be noted that while EPM is being modified to accept data on rotten stumps and logs, live standing and herbacious fuels, and grass and mosses, no data on these fuel types were available for the selected case studies. Table 1 summarizes the available pre-burn load of fuel elements in each example.

Under dry, well-cured, conditions in the Amazon, Washington, and Oregon forest, fuel moistures were assumed to be 25% for 1,000-hour fuels (7.6 cm to 15.2 cm diameter wood) and 10% for 10-hour fuels (0.6 cm to 2.5 cm diameter wood). Burning slash in the Amazon, however, can occur before total drying within 3 months after harvest. In this case fuel moistures are close to 70% in 1,000-hour fuels and 15% in 10-hour fuels. In the cerrado, which tends to be drier than elsewhere, fuel moistures were assumed to be 10% for 1,000-hour and 5% for 10-hour fuels. Ignition of 20 hectare fires was assumed to require 1 hour, except in the ponderosa pine understory burn where it is more usual to burn large areas more slowly so 120 hectares were assumed to ignite in 6 hours. All cases were on flat terrain.

Table 1. Pre-burn fuel loadings (Mg/ha) for each size class of woody fuels and duff depth. Data for case examples from Kauffman et al. (1994), Hobbs et al. (1996), and Ottmar et al. (in press).

			woody	fuels			Duff
	0 to 0.6 cm	0.6 to 2.5 cm	2.5 to 7.6 cm	7.6 to 22.8 cm	22.8 to 50.8 cm	50.8+ cm	Depth (cm)
Amazon - slash	17.6	16.9	38.7	70.6	145.0	0.0	1.3
Cerrado - stand	12.1	0.7	1.0	26.1	1.2	0.0	0.8
Oregon Pine - stand	0.2	3.9	10.2	5.1	7.0	11.4	2.0
Oregon Pine - slash	1.2	5.6	11.6	10.4	15.0	0.0	2.0
Oregon Pine - understory	0.2	3.9	10.2	5.1	7.0	11.4	2.0
Washington Fir - dry slash	6.3	10.4	17.4	52.9	118.7	73.2	7.1

Figure 4 shows results of the EPM test-runs for three types of tropical burns. In the Amazon primary forests, many trees are harvested during land clearing. This removes large logs and limits smoldering. Usually burning takes place within 3 months of logging before the wood has completely dried. This wet-slash type of burn emits nearly 7,000 grams per second (g/s) of particles during its flaming phase, which is followed by a short smoldering phase. When fuels are completely dry, usually one full year after harvesting, nearly 11,000 g/s are emitted in a flaming fire and there is almost no smoldering component. In the cerrado, where small trees and grasses are burned prior to any working of the landscape, so-called stand-replacement fires emit about 4,500 g/s during the flaming stage and a short smoldering phase follows.

In the United States, emission rates from four types of fires are shown in Figure 5. Slash burning in the temperate rain forest of the Olympic Peninsula in Washington State is comparable to the burning of dry slash in the Amazon rain forest, with over 11,000 g/s emitted during the peak flaming stage. A very long smoldering period continues because of deep duff layers that accumulate in old-growth Douglas fir forests and the large old stumps and rotten logs left over from a bountiful harvest. Significantly less smoke is emitted from fires in the interior Pacific Northwest. In the ponderosa pine forests of northeastern Oregon, the smoke from burning harvest residue and stand-replacement fires both emit nearly the same rate of particles, about 3,500 g/s during the flaming stage. This rate is significantly lower than emission rates in rain forest slash and somewhat lower than savanna emission rates because the fuel in pine forests are much more sparsely distributed. Understory fires, which are typical of frequent small fires in fire-adapted ecosystems, and the style of prescribed fire used to restore a natural fire regime, show very small rates of particle emissions (less than 400 g/s from the 120 hectare plot) over a long period, reflecting the slow and deliberate ignition rate.

In addition to gas and particles, EPM calculates heat release rates. Therefore, it is possible to estimate the effect on plume rise for each fire. This is an important step in determining the contribution of biomass emissions to the climate system as well as its impact on human health and visibility. Buoyant plumes can carry emissions high into the atmosphere where long residence times are possible, furthering the potential for chemical changes that affect radiation and create ozone. Less buoyant plumes cause emissions to remain relatively close to the ground, compounding human health issues and causing visibility problems that degrade transportation safety and scenic vistas. In estimating the global impacts of biomass burning, Liousse et al. (1996) showed that injection height of aerosols significantly affects predicted concentrations.

To show the variability that may be possible among different land-use examples, the very simple approximation proposed by Manins (1985) is used to estimate plume rise in a stably stratified atmosphere,

$$Z = 1434 \times (P)^{1/4},$$

where Z = plume rise in meters and P = maximum power in gigaWatts (GW). Manins compared this formula with observed plume heights and approximate power estimates ranging from 20 to 60,000 GW from natural fires, volcanic eruptions, and wartime firestorms. The resulting mean square error was estimated at 30% (Harrison and Hardy 1992). Table 2 summarizes the maximum power modeled by EPM and the estimated plume rise from Manin's formula. From this exercise it is clear that burning dry slash in both the tropical rainforests of the Amazon and temperate rainforests of western Washington create the greatest heat and therefore the highest plumes, reaching close to 3000 meters. Often cumulus and cumulonimbus clouds develop over these large fires and further turbulence and entrainment enhances their buoyancy. Modeled peak power is significantly less for Oregon pine understory burning but plumes from these fires can exhibit reasonable buoyancy shortly after ignition, which usually coincides with maximum power output. The smoldering phase of a fire outputs a fraction of the maximum power and by the time the independent smoldering stage is reached, power is close to 0.1 GW or less, causing plumes to remain well below 800 meters above ground level.

Table 2. Modeled estimates of maximum power from EPM and estimated plume rise from Manins' formula (1985) for each case example.

Fire Type	Peak Power (GW)	Plume Rise (meters)
Amazon - dry slash	17.34	2926
Amazon - wet slash	9.37	2509
Cerrado - stand	4.56	2096
Oregon Pine - stand	4.17	2049
Oregon Pine - slash	5.09	2154
Oregon Pine - understory	0.61	1267
Washington Fir - dry slash	15.91	2864

USING EPM FOR GLOBAL ESTIMATES OF BIOMASS EMISSIONS

The locally derived model, EPM, can be used to estimate global biomass emissions and gain a more complete understanding of the impact of wildland fires. For example, Mack et al. (1996) estimated global biomass emissions by developing a global fire model that estimates burning efficiencies from fine dead fuel moisture and by introducing some ability to model the effects of climate and land-use changes over time. Components that significantly affect the rate and magnitude of emissions, however, were not considered. These include ignition patterns, large dead fuel moisture, and unnatural fuel distributions (e.g., piles and harvest slash), which are explicitly resolved in EPM. Therefore, linking EPM with global models could provide more accurate assessments of the impacts of biomass burning on carbon budgets and the global climate.

In addition to modeling, global emissions can be estimated by remote sensing of smoke. Aircraft or satellite based sensors, however, must make certain assumptions about the character of biomass burns to properly interpret sensed values. For example, Kaufman et al. (1996) assumed a simple model of mixed energy when interpreting data from the 1.6 µm radiation channel on NASA's ER-2 MODIS Airborne Simulator (MAS) over the SCAR-C Quinault prescribed fire, which was the same fire for which we obtained fuel loadings in our idealized case of burning dry harvest residue in a fir rainforest. The MAS-derived mixed-energy results were compared with another approach that considered each pixel as black body having homogeneous temperature. Little disagreement was found and their conclusion was that the derived flux of radiative energy was not very sensitive to assumptions in the interpretation algorithms.

When comparing MAS-derived results with EPM output for the Quinault prescribed fire, however, significant differences were found. For example, heat release rates in EPM rose steeply during the ignition phase of the fire whereas the derived values began instantaneously at about 75% of maximum. According to ground-based observers, ignition occurred in 10 stages over a period of about an hour and build-up was rapid, like the EPM simulation, but not instantaneous. Also, the maximum heat release rate from EPM was about 35% greater than the derived maximum radiative energy. Because EPM models total heat at the source, which includes radiative energy as well as convective energy, and the MAS derived values only consider radiative energy, the difference in maximum heat release rates is expected. Another aspect of radiation measurements affect calculated fire size, which can be overestimated if horizontal fluxes are not considered in the remote sensing algorithms.

In their work, Kaufman et al. (1996) reported that the MAS-derived particle emission rate was about twice as great as the EPM values. This is not surprising because it appears that they used the EPM PM2.5 output, which is only a fraction of total particles. If compared against the EPM total particle emission rate, the maximum EPM rates were about 80% of maximum MAS-derived rates. This is well within the error bounds for both model and remote sensing data.

The MAS-derived radiative energy and particle emission rates reflect similar patterns that are distinctly different than EPM patterns of heat release and particle emissions, especially in the ignition phase of the fire. This suggests problems in the timing and proportion of flaming to smoldering combustion that are used in remote sensing algorithms. It is our belief that use of ground-based observations and models like EPM can improve remote sensing capabilities.

SUMMARY

The EPM test cases show that land clearing and burning of residue slash in dense rain forests (whether temperate or tropical) causes the highest rates of biomass particulate emissions. Also, with comparable heat-release rates (over 15 GW from the 20 hectare plots), plumes from these types of fires are likely to reach high levels of the atmosphere and, therefore, be transported over longer distances. Higher fuel moistures, however, can reduce emissions by 30% or more. Slash burning and stand-replacement fires in dry pine and cerrado forests, where fuels typically are more sparsely distributed, emit less smoke and are less likely to loft above typical mixing heights. Long duration, low magnitude emissions are common in understory burns like those intentionally ignited for ecosystem management in ponderosa pine forests of the Pacific Northwest.

In this paper the EPM model was used to show the distinctive differences in biomass emission rates caused by different land-use patterns. We believe that this type of modeling can provide more accurate estimates of biomass emissions by improving remote sensing algorithms and coupling with global models. For example, errors occur when remote sensing algorithms misrepresent heat release, timing of combustion phases, and the proportion of flaming to smoldering. Likewise, models that neglect ignition patterns, large fuel moisture, and unnatural fuel distributions may produce inaccurate results.

Some caution with these results is necessary. While EPM compares well with tower and aircraft measurements of biomass emissions from broadcast slash burns, and qualitative comparisons between EPM model output and emissions from wildfires, stand-replacement fires, and understory burns appear promising, more quantitative verification is needed. Nevertheless, the EPM model is a viable tool for estimating biomass emission characteristics in a variety of burning styles and fuel structures.

Development of EPM is part of a larger strategy by the Fire and Environmental Research Applications (FERA) team of USDA Forest Service Research to provide one information system that supports; a) single-event risk assessments in fuel management and fire management decisions, b) programmatic risk assessments in developing fire management strategies, and c) large-scale assessments of global change and land-use policy options. Along with EPM, we are developing:

(1) simple techniques (such as Photo Series) to inventory the characteristics of wildland fuelbeds,

(2) Fuel Characteristic Classes to systematically classify fuelbeds,

(3) algorithms that predict the moisture content of fuels based on ambient weather,

(4) algorithms that predict fuel consumption during the flaming and smoldering,

(5) identification of fire severity thresholds (i.e., conditions of non-linearity of fire effects), and

(6) mesoscale climate scenarios, based on historic data or modeled future climates.

These tools are being developed primarily to support fuel management decisions on federal lands, as part of the U.S. Joint Fire Sciences Program. However, companion research is being done along a pole-to-pole "Transect of the Americas" to expand their applicability to all common boreal and tropical ecosystems. We are currently revising the model to modernize its user interface, improve its technical performance relative to long-smoldering fires and non-buoyant plumes, and add data defaults and linkages. We propose use of EPM to develop more precise estimates of global biomass emissions and improved understanding of the impact of biomass emissions on global climate.

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FIGURES

Figure 1. Hourly light-scattering coefficient from measurements taken approximately 4 km down-valley from a 360-hectare smoldering under-story burn in northeastern Oregon. Time is in Pacific Daylight.

Figure 2. Input requirements and computational flow diagram for EPM.

Figure 3. Fuel consumption rate over 0.5 hectare of a typical biomass burn. The thin line shows measured data from sampling packages elevated over the point of ignition. The thick line shows modeled data from EPM.

Figure 4. Modeled emissions for typical fuel loading, fuel condition, ambient weather, and ignition pattern in 20-hectare fires for broadcast slash burning and stand-replacement in two forest types of Brazil.

Figure 5. Modeled emissions for typical fuel loading, fuel condition, ambient weather, and ignition pattern in 20-hectare fires for broadcast slash burning and stand-replacement, and for a 120-hectare understory burn in two forest types of the Pacific northwestern United States.