Физика горения и взрыва, *1996*, т. *32*, № *5*

MATHEMATICAL MODELING
AND PREDICTING WILDLAND FIRE EFFECTS

F. A. Albini, J. K. Brown*

Mechanical Engineering Department Montana State University,
Bozeman MT 59717
*** USDA Forest Service Intermountain Fire Sciences Laboratory,**
P. O. Box 8089, Missoula MT 59807

A qualitative assessment is made of the role of mathematical modeling in predicting the effects of wildland fires. Specific roles for mathematical models of physical processes involved in causing fire effects are identified in creating decision aids for helping managers make better decisions in planning fire use and in strategic planning of wildfire suppression. More direct roles are seen in helping to strengthen our knowledge base about fire effects through more efficient use of research resources. In assessing the potential utility of mathematical models in these roles, a novel taxonomy of wildland fire effects is introduced, based on longevity of the effect, time delay between fire and emergence of effect, and distance between fire and effect. Physical processes are identified as candidates for mathematical modeling, as are factors complicating the realization or use of the models. Candidate modeling topics are identified as

(1) *Heat transfer in and near the fire environment,*
(2) *Combustion processes and products,*
(3) *Heat and mass transport in porous media,*
(4) *Chemical and physical responses of fire heated soils,*
(5) *Erosion and hydrology of fire-affected sites,*
(6) *Fluid mechanics of wind and fires,*
(7) *Transport, dispersion, and aging of fire emissions in the atmosphere, and*
(8) *Global atmospheric effects.*

Then, using the fire effects taxonomy described, qualitative practical limits on the predictability of processes involved in them are deduced by considering contributing complicating factors that are identified as not likely to be modeled reliably. By so doing, the list of candidate topics for mathematical modeling is refined and reduced to the following recommended set. Heat transfer to, and thermal response of, live vegetation parts within and near the fire environment. Heat transfer to soil under burning duff. Heat transfer to soil exposed to fire environment without duff cover. Heat and mass transfer in fire-heated porous media. Physical, chemical, and hydrological responses of soils to high temperature environments. Fluid mechanics of wind fields interacting with fire and vegetation cover.

I. INTRODUCTION

Managers of wildlands are almost certain to face the task of predicting effects of fires on lands under their stewardship. Management objectives ranging from maximizing renewable resource production to custodial oversight may often be furthered by the application of prescribed fires and are variously impinged by unplanned fires. Thus it becomes necessary to predict a variety of consequences before or during a fire, in order to promote desirable outcomes and to avert undesirable ones. Providing land managers with the tools to make the needed predictions has posed a long term challenge to the wildland fire research community.

A major response to this challenge has been the accumulation over the years of a large body of empirical knowledge relating a variety of fire effects to preburn conditions and fire characteristics. Although such relationships may have questionable validity until proven in each new application, they have the appealing features of specificity, minimal data demand, and confidence that the knowledge was derived from experience. It seemed that the slow but certain accumulation of knowledge through the practice of empirical science would ultimately satisfy most requirements on land managers for prediction of fire effects. But demands upon land managers have been escalating for detailed, quantitative planning of all actions on the ecosystems they oversee, while budgets for the research to support such planning are becoming more stringent. And as attention has focused increasingly on environmental quality, demands have risen for assessment of the effects of land management actions upon distant downstream environments, and even globally. These developments suggest that the empirical paradigm for accumulation of knowledge about fire effects must be supplemented with mathematical modeling of physical and biological processes.

We outline here some roles we see for mathematical models in helping to satisfy land managers' emerging needs for the prediction of the effects of wildland fires. It appears that such models might prove useful in helping quantify some fire effects for planning purposes. Our considerations also indicate that mathematical models can be valuable in strengthening the knowledge base in two ways. First, established relationships between parameters can permit more focused gathering and manipulation of field data. Second, models can be used to design laboratory experiments for improved information yield.

We analyze the spectrum of fire effects in several dimensions to discover how mathematical models of underlying physical processes fit into the sequence of cause and effect relationships. Because mathematical models of physical processes invariably deal with the connections of events in space and time, we explore a taxonomy of fire effects based on spatial and temporal attributes. We find that this taxonomy classifies fire effects in a heuristically appealing way and also allows some generalization about probable predictability of classes of effects. This generality stems from the influence of unmodeled chance (or "stochastic") events on various effects and the greater importance of such influences with increased spatial or temporal separation between the fire event and the effect in question. By examining the influence of unmodeled variability of parameters on the processes that might be modeled, one can estimate qualitatively the predictive power such models might achieve.

Finally we attempt to assess the utility of some physical process models that cause events ultimately linked to the occurrence of a wildland fire. We explore such questions as the data demands of the models and practical factors that would limit their value or usefulness. A limiting case that can sometimes be enlightening is achieved by assuming that a hypothetical model created without cost makes error free predictions and has data requirements that are fully satisfied with no effort or expense. This artifice can reveal when a model would have little value because the severity or extent of the predicted effect is dominated by unmodeled processes or because its predictions would play little or no role in the next step of most practical management decision processes.

We recognize that modeling of biological processes such as vegetation growth and plant community succession is paramount to understanding and predicting important fire effects. Our paper, however, focuses mainly on physical processes that affect the fire environment or are a direct result of the fire.

II. THE ROLE OF MATHEMATICAL MODELS IN PREDICTING FIRE EFFECTS

Ideally, if all possible fire effects could be predicted accurately through modeling, we would be in a better position to control adverse fire impacts and to realize beneficial ones. Fire could be used for land management purposes with assurance that the desired outcomes would be achieved and undesired ones averted. Fire suppression resources could be used with utmost efficiency in minimizing undesired fire effects and permitting beneficial unplanned fires to further management objectives.

But in our less than ideal world, nature imposes limitations on our ability to predict events. Thus we must forecast fire effects based upon assumptions which may not be correct and that rely upon some future course of events which we cannot clearly foresee and over which we have no control. Nevertheless, predictions from tested mathematical models of known validity and understood limitations should help reduce uncertainty in the management process. It should also permit quantification of at least some aspects of the process of arriving at "tradeoff" decisions, a perennial chore of managers.

In this section we outline roles for mathematical models in predicting fire effects by citing examples of models we believe should be realizable. In a later section we examine complicating influences on the sequence of causes and effects embodied in the models and explore these implications for limiting the predictive power of various types of models. By this, we illustrate a method of setting priorities to maximize research productivity in developing models.

1. Helping Managers Make Better Decisions Related to Fire. Predictions of significant local and downstream effects that would occur due to fire burning under a set of typical conditions on all the land in a jurisdiction would represent a uniquely valuable resource as an aid to strategic planning of fire suppression and for planning the scope, nature, and schedule of prescribed burning operations.

Such a set of predictions would be realized using of a spectrum of mathematical and empirical models. Some of the necessary empirical models exist [1, 2], but few of the mathematical models do. Whether or not it is a wise use of money and human resources to develop catalogs of potential fire effects depends largely upon the costs of developing the needed models and the predictive power the models might have if developed.

By examining a few examples of the kinds of decisions that would be aided by the use of mathematical models, we sample the scope of the modeling effort and become aware of the phenomenology which must be addressed. One also gains an appreciation for the kinds of decisionmaking challenges faced by land managers and thus some understanding of what might constitute a worthwhile "improvement" in predictive capability from the perspective of the model user.

a. *Aid in Planning of Fire Use.* Using on-site data to adjust the schedules of prescribed fires in order to achieve established burning objectives could be furthered substantially through the use of validated mathematical models. And prediction of effects in generic modeling exercises should assist in overall scheduling and scaling of burning operations. Examples of such uses of mathematical models follow.

Combining use of mathematical models relating surface fire intensity to flame height and wind speed with models relating lethal scorch height to fire intensity and wind speed allows managers to establish guidelines for making onsite decisions about the efficacy of burning to remove understory with minimal overstory impact [3, 4].

Using mathematical models for heat transport in soils [5, 6], fire planners should be able to interpret small sets of soil temperature measurements taken under test fires to predict maximum depths of lethal temperatures for rhizomes, roots, and soil organisms for an entire burn site. Mathematical models for smoke transport and dispersal [7] and for mesoscale wind fields, along with models for fire spread rate [8, 9] and emission source intensity [10], would allow the impact of proposed air quality regulations on burning schedules to be assessed through office exercises conducted during slack fire season.

b. *Aid Strategic Planning of Fire Suppression Actions.* Most tactical planning of fire suppression actions omits consideration of fire effects except indirectly. But the strategic decisions behind all fire suppression activity are firmly rooted in consideration of fire effects. Indeed the decision to forgo any suppression action or to initiate prescribed fire, especially for areas where natural disturbances are desired to maintain the character of the resource, is based almost exclusively on consideration of likely fire effects [11]. So consideration of fire effects in strategic planning of fire suppression is not a novel concept. But we see extensions to be made through quantitative economic assessments based on prediction of fire effects, as in the following examples.

Mathematical models for fire growth [12], used in combination with weather forecasts and models predicting tree mortality as a function of fire behavior parameters and timber stand descriptors, should allow quantitative cost-plus-loss comparisons of the economic costs of allocating firefighting resources to competing uses.

Mathematical models for ignition, extinction, and rate of spread of smoldering combustion in peat should allow an economic comparison of alternative strategies for attacking a peat bog fire [13]. Using additional models for production and transport of gaseous and particulate products of combustion would permit assessment of the air quality impact on nearby populations as an additional consideration or constraint.

A fire in uneven aged mixed conifer timber increases in intensity during the day when it spreads most rapidly. Using mathematical models for fire behavior, the growth of the fire can be forecast and predictions made of the vegetation that will be burned if no suppression action is taken. Extending the modeling to include prediction of tree mortality would allow a prediction of the post-fire species composition and stand age distribution, and thus an economic assessment of the timber value loss to the fire, or the breakeven cost of suppression.

2. Helping Strengthen Our Knowledge Base. Mathematical models can be used to help narrow the ranges of variables in field research and to help focus data processing efforts in the quest for empirical relationships. The same basic approach can be applied to guide the design of laboratory experiments for greater productivity. Here are some examples of the kinds of uses we see for mathematical models in these roles.

a. *Focus Field Data Gathering and Manipulation.* A mathematical model for heat transfer in duff and soil might be used to find minimum surface fuel consumption required to have an effect on temperature history in the soil. Minimal measurements to verify this bound could free resources to concentrate measurements in more heavily loaded burn units. A mathematical model for chemical reactions in soils versus temperature would permit prediction of surface layer pH as a function of maximum depth of an isotherm. Such a relationship would provide a rationale for the grouping of data on duff and surface fuel reduction and soil moisture and how such variables should be combined to explain soil pH data variation.

b. *Guide Design of Laboratory Experiments.* Mathematical models for percolation of water into soil and for sediment transport by runoff would allow assembly of a model for soil erosion versus slope, amount and rate of precipitation, and soil texture. This kind of model can be tested and validated in a laboratory setting and could then be used with confidence in the field.

A mathematical model for the rate of burning of woody fuels yields the functional dependence of burning rate on fire temperature, fuel mass density and moisture content to within scaling factors that can be found by laboratory measurements. This example has already been realized and the results incorporated in a model for the burning of large downed woody fuels [14].

A mathematical model for heat and mass transport in fire-heated moist soil can be used to guide the selection of the range of variables for a series of laboratory tests to be conducted to perfect and calibrate field instruments.

III. A TIME-AND-SPACE TAXONOMY OF FIRE EFFECTS

In this section we categorize fire effects in terms of spatial and temporal domains. Later we examine important mechanisms linking effects to fire events with this taxonomy in mind, and identify factors that tend to spoil the predictive power of models of this linkage. The resulting list of connections constitutes a framework in which priorities can be set for the development of mathematical models and for ordinating their relative values.

We create this nontradiational taxonomy of fire effects by grouping them into categories that measure longevity of effect, time delay between occurrence of fire event and realization of effect, and distance separating fire site and effect locale. Examples are given of effects that typify categories. The set of examples is not encyclopedic and neither is the categorization unique. That is, not all possible fire effects are listed, and some of the effects cited may belong to more than one of the various categories.

1. Longevity of Effect. Fire effects last for periods of time that range from the duration of the fire event to geological scale. The following categories are offered as candidates which represent a natural parsing of this dimension.

a. *Transitory: Effects Last Only about as Long as the Fire Event.* Examples — Local air quality degradation can pose a potential health hazard and impair air and motor vehicle traffic. A rainstorm may be induced by the convection column of a large fire.

b. *Seasonal: Effects are Largely Limited to One Growing Season or Less.* Examples — The current crop of herbaceous vegetation might be removed from the fire site, reducing herbivore forage temporarily, but increasing forage yields in future years [15]. There would also be a temporary reduction of cover and food for birds and small mammals, but possibly an increase in food in future years. The albedo of the earth can be temporarily altered locally by a fire covering a large area.

c. *Multiyear: Effects Endure for Several Years.* Examples — Pattern and amount of water runoff from a fire site may be altered by removal of tree and shrub cover until it regenerates. The species composition and physical structure of plant communities evolve from seral to climax character [16]. Large fire-killed trees may host an increased cavity nesting bird population while they are still standing. Properties of soil may be altered by heat treatment. Chemistry of trace air constituents may be influenced on a global scale [17].

d. *Long Term: Effects are Epochal Events.* Examples — A stand replacement fire initiates long term sucessional changes in forested areas and in the economy of local human communities. Fires can reshape the landscape thus altering land management practices and resource goals through the action of political and economic forces.

e. *Geological: Effects are Irreversible on Human Time Scale.* Examples — Fire, geomorphic processes, and landforms interact to shape landscape patterns [18]. For example, fire deep in organic soil of a swamp or bog may result in the creation of a lake. Erosion of steep terrain following a severe fire may remove all top soil and permanently alter the landscape.

2. Time Delay between Fire and Effect. When an effect of a wildland fire becomes evident, it can be measured. At this time it becomes a candidate subject for mathematical modeling because it can then be related quantitatively to other relevant measurables. Here we consider some time periods that are representative of delays between fires and times when particular effects become evident.

a. *Prompt: Effects Become Measurable no Later than a Few Days after the Fire.* Examples — Local air quality effects are essentially coincident with fire occurrence. Reduction in loading of surface fuel, including litter and duff, immediately exposes mineral soil to airborne seed. Mortality of or thermal injury to vegetation is measurable quite soon after a fire.

b. *Delayed: Effects Occur within a Few Years of the Fire Event.* Examples — Loss of minerals from burn site by leaching and through ash blown by wind; increased yield of annual-growth forage from temporary mineral enrichment; increased silt burden in watershed streams due to enhanced erosion of fire site. Insect activity may increase in thermally injured forest stands. Fish production of watershed streams may be reduced because of loss of riparian trees and shrubs, or it may be increased due to improved nutrient regimes and improved stream habitat [1]. Carbon sequestered in fire-reduced forest biomass increases atmospheric CO_2 burden at least temporarily. Large scale forest fire may eliminate tree disease, parasite, or symbiont regionally.

c. *Derivative: Effects Attributable (at Least in Part) to Fire Occurrence Evolve over Long Periods of Time.* Examples — Reduction (or increase) in predator species population because of fire-induced reduction (or increase) in habitat or food for prey species. Recurrent stand-replacement fires inhibit evolution to climax forest and lead to seral species dominance.

3. Distance between Fire and Effect. Fire effects vary over an extremely wide range of distances between fire site and location(s) at which the effect is realized. The following three categories of distances seem to us appropriate for classifiying fire and effect separation.

a. *Local: Effects are Restricted almost Totally to the Burned Area.* Examples — Fuel consumption reduces fire hazard by removing fuel and lessening resistance to control; vegetation mortality increases fire hazard by increasing the loading of dead surface fuels. Site productivity changes may shift patterns of wildlife use.

b. *Downstream: Effects are Felt in the nearby Downstream Watershed and/or Airshed of the Burned Site.* Examples — Dense smoke accumulation may force closure of an airport for safety reasons. Flyash fallout can render pasture grass unusable by herbivores. Stream siltation may force municipal water authority to accelerate maintenance schedule. Landscape visual impacts can reduce sightseeing visits to a scenic area that is burned over.

c. *Widespread: Effects may Extend from Regional to Hemispheric.* Examples — Increased sediment burden from a single watershed may harm anadromous fishery on a regional scale. A very large fire may temporarily alter the earth albedo over a large enough area to shift regional rainfall patterns, causing flooding. An extremely large fire (or a large number of smaller ones) may sufficiently increase the atmospheric CO_2 burden to raise mean annual hemispheric temperature by enough to influence climate.

IV. PRACTICAL LIMITS TO THE PREDICTIVE POWER OF MATHEMATICAL MODELS

In this analysis we attempt to place within broad limits the influences of the unmodeled — and perhaps unmodelable — variation of parameters and stochastic processes that modify the causal connections between fire phenomenology and fire effects. We approach this analysis by listing a collection of physical processes appropriate for mathematical modeling; each of the processes plays a role in connecting some fire effect(s) to some fire phenomoenology that gives rise to them, as should be apparent.

We identify deviations from uniformity, homogeneity, and isotropy, and variability in intrinsic properties of media, and of boundary conditions, etc., which can be expected in natural settings. These complicating factors tend to spoil the predictive power of the hypothetical mathematical models. They have sometimes been described, inaccurately, as stochastic influences, because they result in a loss of predictive precision that is similar to the effects of perturbations which occur with some degree of unpredictability over the course of time.

1. Physical Process Models and Complicating Factors. The physicochemical processes taking place during the event of a wildland fire are relatively simple and few in number. Heating of solid vegetable matter liberates its adsorbed and intercellular moisture and eventually raises its temperature to the point at which decomposition (pyrolysis) reactions take place. These solid phase reactions do not require the input of a great deal of energy to initiate them; they reduce the solid matter to carbonaceous char that has an increased heat of combustion. The reactions also yield combustible and noncombustible gaseous products, some of which promptly condense to form liquid droplets generically labeled "tars".

The combustible gases may burn, creating mostly CO_2 and water vapor, but also a host of incomplete combustion products, including soot. The carbonaceous char may burn in complex heterogeneous combustion processes, producing large amounts of CO as well as CO_2 and water, and leaving solid mineral ash, the oxides of trace metallic elements in plant tissue. If heat is generated only through heterogeneous reactions, the process is called smoldering combustion. If gas phase reactions generate significant heat, glowing particulate matter in the gas flow creates visible flames and the process is identified as flaming combustion. While the details of the chemical processes are exceedingly complex, most of the details are largely irrelevant in determining the effects of the fire on the environment. The process can be viewed as the reaction of vegetable matter and Oxygen, releasing heat and creating a variety of gaseous and solid products.

The gaseous and entrained particulate products disperse into the atmosphere, perhaps significantly degrading air quality locally, possibly influencing local mesoscale meteorology, and affecting atmospheric chemical processes on a regional or even larger scale. The ash residue results in a prompt reduction of soil acidity on the burn site.

The amount of biomass removed and left on the burn site can have important consequences of both a positive and negative nature. Excessive loss of the litter and duff mantle may increase soil erodability by wind and precipitation runoff, as can loss of grass and shrub cover. Removal of the litter and duff mantle may also favor regeneration of diverse flora and provide a flush of nutrients for establishing plants. Reduction in volume of large woody material on the surface can have important biological consequences such as alteration of the local microclimate and soil organic materials [19]. And often the most significant phenomenon initiating the stream of consequences flowing from a fire event is simply the release of heat.

a. *Heat Transfer in and near the Fire Environment.* Thermal effects of wildland fires can be predicted if heat transfer to the target medium or component can be calculated in advance using a measured, inferred, estimated, or predicted description of the fire environment. Thermal effects on live vegetation are often of interest or of great importance in establishing conditions which in turn determine the ultimate effect of interest. The heat transfer mechanisms involved above the surface are radiation and convection, while below the surface, in soil, the mechanisms are conduction and mass transport.

Models can be constructed for heat transfer to live foliage and through a bark layer to cambium, given the necessary fire environment descriptors. These models would provide such items as the height above the surface to which live foliage would be lethally scorched and the minimum bark thickness to insure cambium survival (or its converse, maximum bark thickness with cambium kill) as a function of height above the surface, keyed to fire environment descriptors. The depth of penetration of the lethal isotherm into moist soil under a fire would be predicted by a model for heat transport within the soil, but it would have to be based upon the heat transferred to the soil under the duff mantle, and for this an entirely different prediction model is required.

Estimation of aboveground heat transfer is complicated by variations in the structure of the fuel complex, variations in fuel conditions, and, perhaps most importantly, by wind speed and direction variations. If the fire is burning off part of the vegetation cover layer, it is simultaneously modifying the interaction of the wind and the fire, further complicating the process. Belowground heat transfer is modified by fire behavior variation as well, but is probably dominated in most instances by variations in the properties of the duff mantle. If the duff mantle is thick and moist, it can form an insulating barrier that prevents heat transfer to the underlying soil. If it is absent (as it would be in a forest opening) then it cannot play this role [20]. But if it is readily burned, the duff mantle can become the dominant source of heat input to the underlying soil. In this instance, the complicating feature of wind speed variation and its influence on duff burning can be extremely important.

b. *Combustion Processes and Products.* Models for the rates and yields of combustion processes would apply to thermal effects at the burn site and effects related to fuel reduction, to air quality downstream, and to atmospheric chemistry effects on a widespread scale. The models would represent "source terms" for other models in many cases. Models for woody fuel ignition and combustion with varying degrees of complexity have been presented periodically over the years [21–25], but we are unaware of any mathematical modeling effort to predict the yield or rate of production of solid and liquid particulate. As the pyrolysis reaction does not demand excessive energy input [24, 26], the progress of the pyrolysis reaction zone through solid woody material should be predicted by the pattern and rate of heat input to the fuel element, suggesting that flaming combustion of woody fuel is a modelable process. Factors complicating the predictability of this process include the nonuniformity of fuel moisture content distributions in larger fuel elements, wide differences in fuel moisture contents and thermochemical responses [26] of living, dead, and decaying fuels, and the variability of heating rate with time and place on small scales within the fire environment, at least some of which would be attributable to variation in wind speed and direction. But it would seem that such models could be appended to or incorporated into existing models for fire spread [27, 28] as a means of demonstrating feasibility.

Smoldering combustion is perhaps conceptually simpler to model, but is uniquely beset by confounding variabilities, among which are: nonuniform properties of the medium; voids and cavities due to animal actions; inclusions of various sizes, shapes, and properties; high sensitivity to wind speed (because the process rate is usually limited by diffusion of Oxygen); and succeptibility to large changes in moisture content from precipitation because the process can last from days to months. Even so, models already developed [29] should be applied and tested for use in predicting fire effects.

c. *Heat and Mass Transport in Porous Media.* Transfer of heat into the soil of a burn site should be amenable to mathematical modeling. Such modeling would allow prediction of the temperature history as a function of depth below soil surface as a function of the heat release history on the surface. With this prediction in hand, a host of biological, physical, and chemical responses to the thermal environment would be possible, from which not only onsite but downstream (mineral leaching, water runoff, soil erosion, etc.) effects could be anticipated. As heat transport in fire-heated soil cannot be modeled realistically without taking into account the heat transported by water vapor movement, heat and mass transport must be modeled simultaneously [30, 31].

Variation in the local heat release rate over the site as a function of time, as well as in local soil properties and moisture content distribution with depth, would lead to a considerable amount of "chance" character in the temperature profile histories realized at different places on any given burn site. But making predictions over the range of parameters expected on site, weighted by their relative abundances or frequencies of occurrence, would allow prediction of the distribution of effects if not a map of their realizations.

d. *Chemical and Physical Responses of Fire-Heated Soils.* The effects of heating on a soil layer can be classified in a variety of ways, depending upon the particular application [32]. Organisms that live within the soil may be killed and organic matter incorporated in the soil may be burned. The demise of soil organisms can probably be predicted accurately from the temperature history of the soil, and the burning of organic matter is proper subject matter for a combustion process model. Other responses can probably be described in terms of chemical and physical responses to the thermal environment. Volitalization, melting, chemical reaction, agglomeration, fragmentation, etc., are processes that can be described in terms of the initial physical and chemical makeup of the soil, its moisture content, and its thermal history. Gaps in this knowledge base are obvious candidates for laboratory experimentation.

These models would use the temperature history predictions of heat and mass transport models if the chemical and physical responses of the soil do not modify the constitutive parameters controlling heat and mass transport. If they significantly affect these transport processes, then it would be necessary to merge the two models into a single entity that would predict the thermal history of the soil and describe its physical and chemical responses to that thermal environment simultaneously.

Those same factors that impede the predictive power of models for heat and mass transport would, of course, impinge the models for soil responses to the thermal environment history. In addition, nonhomogeneity of chemical and physical properties that might be inconsequential for the prediction of heat and mass transport could spoil the predictive power of a model for chemical and physical responses.

e. *Erosion and Hydrology of Fire-Affected Sites.* When a fire consumes surface vegetation and/or the forest floor material, it alters the vulnerability of the burn site to erosion by water, especially on steep terrain where water runoff tends to concentrate into fast moving streams. Vulnerability to wind erosion is increased also, although the influence of terrain is different in this case. In addition, the fire that removes the vegetative protection can also alter the physical character of the underlying soil, thus changing its intrinsic vulnerability to wind and water erosion and, perhaps more importantly, its permeability to water [33].

By changing the surface permeability to water in the burned area, the hydrology of a large downstream region can be affected. Subsurface aquifers can be denied their usual infusion of water percolating from the surface during the season of rainfall or snowmelt, leading to late season water shortages following excessive surface runoff. Conversely, subsurface aquifers can become conduits of extra large volumes, leading to the appearance of new springs or unusually persistent seeps that can adversely affect pasturage or agriculture, while surface runoff fails to provide adequate volume for irrigation and livestock use.

Mathematical models for soil erosion processes exist, as do hydrological models of considerable sophistication [2]. Such models can be applied to make quantitative predictions of the effects of changes in surface cover and surface soil layer permeability. The principal source of uncertainty in the predictions of such models probably resides in the meteorological inputs they require. Water erosion models and hydrological models need much the same information, such as type, amount, and duration of precipitation in the area and diurnal temperature histories. Wind erosion predictions rest on even more uncertain foreknowledge of the degree of soil surface exposure, surface soil moisture content, wind speed, duration, and sometimes direction. Clearly uncertainty of meteorological input data limits the predictive power of these models.

f. *Fluid Mechanics of Winds and Fires.* Fluid mechanical modeling of wind interacting with a uniform vegetation cover layer is deceptively complex, but analytical models have been put forth [34]. If the vegetation cover layer is nonuniform because part of it has been burned in a fire, the problem is even more complex. Including the generation of gaseous combustion products and the release of heat at the active edge of a wildland fire combine to make the job of modeling the fluid flow field there a singularly challenging one. Nevertheless, computational models of this complex phenomenology exist [18] which provide three dimensional, time dependent maps of the velocity, temperature, and turbulence intensity fields.

These predictions, supplemented by knowledge of the radiation intensity field, enable detailed modeling of the thermal responses of any plant parts exposed to this environment. And by extending the modeled region of the wind field downstream, the environment for the transport and dispersion of smoke particulate and other combustion products is achieved.

All these fluid mechanical computations can be performed today, including prediction of the radiation intensity field and the intensity and rate of movement of the fire [18]. Thus only a modest extension of the computations would be needed to create a picture of the prompt thermal effects on the vegetation in the fire region that is not burned. Such predictions as the height of lethal crown scorch or bark thickness required to prevent cambium kill as a function of height above ground should be natural extensions of such models.

Wind field variation with space and time impose limits on the “accuracy” of these kinds of predictions, as do uncertainties in the fuelbed description. It is necessary to describe the mass loadings, geometrical properties, thermochemical properties, moisture contents, etc., of all the fuel components in order to apply such models. In rare cases, such as field research exercises, these quantities may be measured before the fire takes place. But even in prescribed burning these quantities will only be roughly estimated. And in wildfire situations, they may be known only notionally, and the wind field descriptors may be estimates based on field observations and/or on measurements made hundreds of kilometers from the fire site. It will take substantial advances in our ability to infer the required data from simple remote observations to make any significant improvement in the practical limits of predictive power of these complex models. They will, however, continue to find important use in establishing linkages between contributing factors and fire effects for a variety of applications.

g. *Transport, Dispersion, and Aging of Fire Products in the Atmosphere.* Assessing a single fire's impact on the air quality of a nearby site over a short period of time is not a challenging technical feat. Relatively simple models for transport and dispersion of particulate [35], coupled with fire spread rate predictors [18, 34, 36–38], models for fuel consumption by extended burning [14], and estimators of particulate yield [39] should perform satisfactorily in this role. Fire products are essentially inert flowfield markers over the short term, so transport velocity is essentially a map of the wind field. Dispersion is dominated by the action of turbulence in the atmosphere, of which adequate models exist for time spans on the order of a day or less [40].

As time goes on, however, the fire products change character. Some particles conglomerate and begin to drift earthward as they become heavier. Some adsorb water or serve as condensation nuclei and may be washed from the atmosphere by precipitation. Carbonaceous particles absorb sunlight and water absorbs infrared radiation, which can increase the local temperature and lift the plume flow. And, as time goes on, the wind field transporting the products evolves, varying diurnally as well as spatially, even under boringly invariant synoptic conditions. Finally, as there are often simultaneously more fires than one in a fire-prone region, effluent from several sources may be mingled at the impact assessment site, further complicating the problem.

While modeling capability in this general field is strong and increasing, weaknesses remain in our understanding of phenomenology (e.g., aging of particulate) and there remain the primitive input uncertainties of the fuel description which impose practical limits on achievable accuracy. Until the capability to forecast weather, including wind speed and direction over time, improves substantially, any projection beyond one week must be viewed as largely speculative at present [41].

h. *Global Atmospheric Effects.* Although the subject of global atmospheric change has recently received much attention and the contribution of vegetation burning to such a process discussed from a variety of perspectives [39], neither of the authors pretends expertise in the technical disciplines of this topic. It is clear, however, that if combustion products from wildland fires play a nontrivial role in the thermal balance and chemical cycles of the atmosphere, the products must exist in the atmosphere at the appropriate locations, in sufficient concentrations, and at the requisite times, in order to do so. To measure the contribution of wildland fire combustion products to such phenomena as variations in abundance of stratospheric Ozone, variation of the global atmospheric CO_2 burden, or perturbation to the infrared radiation budget of a hemisphere requires modeling on considerably larger spatial and temporal scales than anything discussed above.

Indeed, the models discussed above for the generation, transport, dispersion, and aging of wildland fire products are considered to be on a scale below the spatial resolution of the fluid mechanical models needed to predict phenomena on a hemispheric scale [42]. These fluid mechanical models usually treat elements of the earth's surface measured in hundreds of square kilometers as being indivisibly small and their atmospheric layers' compositions as being uniform and homogeneous. And the model time domains extend over large portions of years at least, so fire events may often be on a time scale that is also below model resolution.

Therefore, accuracy limits on the predictions made by these sorts of models cannot be attributed to the flaws in models of burning processes, the generation of products, or their local transport and dispersion. Fundamentally, all that is asked by the upper echelon models of those at the level of the fire event is a prediction of whether or not the products from a fire promptly reach the stratosphere, and the total quantities injected into the atmosphere of a set of compounds or particulate constituents of particular interest or importance. Some elements of the panoply of unmodeled perturbing phenomena that can upset the predictions of such models become apparent on reflection: Volcanic eruptions, cloud dynamics, solar flares and charged particle storms, etc. So in this instance, it may be that modeling of fire related phenomenology is sufficiently advanced to afford useful input data to models that address global atmospheric effects. These inputs may be distressingly uncertain to the fire phenomenology modeling community but of acceptable precision from the perspective of the user community. This conjecture merits further consideration.

2. Likely Limits on Predictability of Processes. Here we summarize our ruminations about the probable practical limits on the predictive power of the models sketched above. The summary is given in terms of the space and time taxonomy of effects described in the previous sections because it seems to divide the models into groups that have similar limits on their practically realizable predictive power.

a. *Longevity of Effect.* Mathematical models can be used in predicting fire effects that cover the entire range of longevity categories. The practical limits that we see to predictability of the modelable physical processes important to effects of various longevities vary with the nominal longevity of the effect, however.

Effects that are transitory or seasonal in duration are largely controlled by conditions at the time of the fire and thus are least affected by unpredicted or unknowable influences that modulate them. If the physical process models are employed using valid data at the time of the fire, the predictions would probably not be limited by unmodeled events. The same is true of long term and geological scale effects, at least in terms of the prediction of preconditions for the occurrence of such long-duration effects. The occurrence of an epochal fire in an old-growth forest is apparent as it is happening, and is as predictable as is the concentration of smoke particulate the following day at a downwind population center. In the case of effects that depend upon the occurrence of another event, such as heavy rainfall to cause severe erosion on a site denuded of vegetation, the erosion itself may not be predictable, but the occurrence of conditions permitting it to happen is predictable at the time of the fire to the same level of certainty as the severity of rhizome mortality due to thermal effects.

On-site intrinsic variability of conditions will lead to substantial variation in many cases, but the relative importance of such variability will be most important for transitory or seasonal effects, and probably negligible for effects of longer duration.

It is somewhat ironic that the more persistent the effect, the less likely is its prediction to be marred by intervening unpredictable events. To some level of veracity it can be said that both inconsequential and catastrophic effects are more "predictable" than are the complex consequences of multiyear duration. The examples of such effects cited above are typical of these consequences of fires. It is apparent after reflecting on effects of such duration that they represent scenarios of evolution, depending for the specific courses they follow upon a sequence of events that can be influenced, if not controlled, by externalities. These externalities can be independent of both the fire event enabling the start of the sequence and the subsequent history of the fire site environment that physically conditions it for one or another of some number of possible scenarios. The epochal or more intense environment-shifting effects establish their own major courses of evolution by precluding others.

b. *Time Delay between Fire and Effect.* This parsing of fire effects rather precisely parallels the predictiability of the mathematically modelable process at play. The prompt effects, of necessity, are determined by conditions during and immediately following the fire, so predictability in this category is dominated by intrinsic on-site variability and details or peculiarities of nearby downstream perturbations. Events or processes of a stochastic nature have not enough time or space to exercise their influence over the course of events controlling prompt effects, so can be considered essentially static for purposes of predictive mathematical modeling.

Delayed effects that become measurable only after a season or longer either require intervening meteorological events (leaching, erosion, chemical processes) or are tied to biological processes that occur over some period of time. In the first instance, climatological data should allow probabilistic statements about the occurrence of conditions and the development of effects. But in the latter case, systematic ecologists will usually make only guarded projections of the course of events on the basis of biological models without on-site study in the post-fire condition. There are so many degrees of freedom in biological processes, especially where mobile animals are involved, that it is poor science and even worse management practice to extrapolate beyond the proven domain of predictability in such cases.

Derivative effects suffer from these same afflictions only moreso. It is our present assessment that there is little to be gained from the exercise of physical process models to predict effects that will remain unmeasurable for multiyear periods of time following the event of the fire. We can but conjecture concerning the relative influences of chance events and predeterminable conditions arising from physical processes arising from the fire, but our judgment is that whatever predictability remains after many years will be of no consequence to management decisions that must be made long before the effects can be measured. Only in those instances calling for a comparison between dissimilar locales or the planning of fires under substantially different conditions, etc., would physical process models likely prove to be of managerial benefit for effects with this time delay.

c. *Distance between Fire and Effect.* There is some similarity between separation in time and separation in distance between fire and effect, in terms of the degradation of predictability of physical processes. But the analogy is rather weaker than one might at first suppose. We estimate, for example, that downstream airshed and downstream watershed effects which occur promptly suffer only slightly in terms of predictability compared to local phenomenology. To the extent that intervening changes of wind or weather cannot confound the modeling effort, downstream locale should not degrade physical process predictions much, if any, over what can be accomplished for local effects.

Again in this instance, on-site intrinsic variability of conditions should give rise to plenty of case-to-case and time-to-time variability under nominally the same conditions, but this practical limit probably constrains managerial utility of the models in ways indpendent of the source/locale separation issue.

When the distance scale is expanded to regional or global, the kinds of models needed to make predictions of effects are altogether different from those applicable on a local or downstream scale. Because of this, loss of predictability probably arises from causes beyond the scope of this investigation, leaving us free to speculate that the kinds of models discussed here would probably not limit the predictive power of global scale models (see discussion above).

V. SUMMARY

We believe that there are roles for mathematical modeling in prediction of the effects of wildland fires. Such models would find application in the design of field and laboratory experiments and in the organization, analysis, and interpretation of data. They could also be used as basic building blocks for decision processes supporting prescribed fire planning and as components of analyses of the effects of wildfires to aid in strategic planning of fire suppression actions and assessment of options.

The kinds of models thought most likely to prove to be useful deal with phenomenology and effects that are realized promptly or after a brief delay, and do not depend upon a sequence of events extending over any significant period of time. Models that deal with conditions at or near the fire site we feel are also more likely to find early use and to suffer fewer practical limitations on predictive power.

Specific suggestions for model development are offered here with the admonition that these recommendations are the result of the authors' personal speculations only and do not represent official endorsements by the agencies they represent. We suggest that the following topics merit mathematical modeling tailored to the prediction of fire effects, and apologize to the authors of such models of whose work we have not become aware:

Heat transfer to, and thermal response of, live vegetation parts within and near the fire environment.

Heat transfer to soil under burning duff.

Heat transfer to soil exposed to fire environment without duff cover.

Heat and mass transfer in fire-heated porous media.

Physical, chemical, and hydrological responses of soils to high temperature environments.

Fluid mechanics of wind fields interacting with fire and vegetation cover.

Such models are intrinsically complex, since they deal with nature's processes instead of with the artificial industrial world of man's construction. It takes considerable labor and dedication to create mathematical models of natural processes and one must be prepared for frequent failure. But the occasional successes are the more rewarding for it.

VI. ACKNOWLEDGEMENT

The senior author gratefully acknowledges sponsorship of this research by USDA Forest Service Intermountain Research Station under research grant INT-92754-GR and under research joint venture agreement INT-94947-RJV.

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Поступила в редакцию 25/III 1996 г.