Invited Lecture

An Overview of Research on Wildland Fire

FRANK A. ALBINI
Department of Mechanical and Industrial Engineering
Montana State University
P.O. Box 173800
Bozeman MT 59717-3800 USA

ABSTRACT

This paper outlines the subject matter of research on the physics and phenomenology of wildland fire, focusing on topics that bear upon issues of fire control and fire safety. Motivations for research on fire phenomenology are identified as arising from the activities necessary to achieve fire-related objectives, including acceptable levels of fire safety. Differences in the activities, techniques, and tactical objectives for control and prevention of fires in natural fuels and in manmade structures are noted. Sources of wildland fire research information and operational planning aids are identified, and some cautions are ventured concerning their use by nonspecialists.

KEYWORDS: Wildfire, wildland fire, natural fuels

INTRODUCTION

In preparing an overview of research on wildland fire, it is tempting simply to survey the literature of the field, outlining areas of investigation, pointing out significant findings and tracing the development of knowledge from early investigators to the present state of the art. But to bring such a survey to this audience of distinguished scientists with research interests in fire safety poses a unique challenge. This is because, while this group's efforts are focused mainly upon fire in manmade structures, many of its studies are relevant to, and are applied in, modeling of wildland fire phenomenology. But the converse does not seem to be the case. Results of wildland fire research are seldom cited in the literature of fire safety research as it is done by this audience.

The reason for this asymmetry may be that the literature of wildland fire research has, until recently, been either dispersed in a wide variety of archival journals, sequestered in uncirculated government agency publications, or bound into obscure and unobtainable technical conference proceedings. For example, periodicals that have published papers on wildland fire over the past few decades include journals on combustion, heat transfer, fluid mechanics, engineering, computer applications, forestry, ecology, meteorology, applied mathematics, and pure mathematics. Government agencies perhaps unfamiliar to this group but which routinely publish wildland fire research include USDA Forest Service Research Stations (formerly Forest and Range Experiment Stations), Canadian Forest Service Regional Offices, Australian CSIRO Divisions, the St. Petersburg Forestry Research Institute, and the Krasnoyarsk Wood and Forest Institute of the Siberian Section of the Academy of Sciences of Russia (formerly USSR). Periodic conferences of which this group may be unaware, but which usually include high-quality technical papers on wildland fire include the Tall Timbers Fire Ecology Conferences sponsored by the nongovernment Tall Timbers Research Station, Tallahassee Florida, and the biennial American Meteorological Society - Society of American Foresters joint conferences on Fire and Forest Meteorology, the 13th of which was held last year in Lorne, Australia. A multitude of interagency task forces, working groups, and cooperative teams dealing with wildland fire issues have been created and have produced compends of practical techniques, handbooks, training materials, and even research agendas. Such intramural activities are almost invisible even to the interested professional. Thus wildland fire research, almost exclusively the province of government research laboratories, has been largely a hidden endeavor. Comprehensive books summarize the subject matter periodically [1-5], as do occasional surveys [6-10].

Interest by the general public in matters of wildland fire safety has grown with the increased exposure of affluent society to the hazards posed by building flammable structures in flammable wildland settings. This interest, in turn, has stimulated increased attention to the field by academic and industrial research communities. The expanded interest is welcome and, in the view of this author, long overdue. The field now has a semiannual international news letter (International Forest Fire News) edited by Prof. Johann-Georg Goldammer of the University of Freiburg and published by the United Nations in Geneva. It also supports the International Association of Wildland Fire (IAWF), which publishes a quarterly journal, a news magazine, and occasional monographs and markets a substantial library of books dealing with wildland fire. The current issue of a computer data base published by IAWF includes 50,000 literature citations and the names and addresses of 90,000 individuals with some level of interest in wildland fire research. Many of these names are familiar to the attendees of this symposium, and it is likely that most of the attendance roster will be found there.

This focused and enhanced exposure of wildland fire research may stimulate greater interchange between the urban and wildland fire science communities. Whether active research collaboration ensues or not, it is inevitable that we each shall become more familiar with the other's specialty, just as firefighters on the ground are doing [11]. In spite of the asymmetry of research awareness mentioned above, the learning burden in this process will probably be greater for wildland fire specialists than for traditional fire safety science researchers. This is because the latter group strongly favors mathematical modeling of physical processes while wildland fire research traditionally incorporates a significant component of empiricism, often only weakly supported by conceptual models of underlying physical processes (compare, for example [12] and [13]). In what follows, the sources of divergence of research emphases are explored, as a guide to describing the wildland fire research agenda and approaches taken in its prosecution.

RESEARCH MOTIVATIONS

One may look for motivations of research on fire phenomena in the objectives of human activities involving fires. Of course, fundamental research on various physical, chemical, thermal, and fluid mechanical processes that may be involved in fires is not inconsequential, nor must all fire research necessarily be directed toward achieving any specific goal identified below. But the basic motivations identified help to establish the level of emphasis placed on various efforts, influencing the setting of priorities and budgets to do the research.

As a specialist in the modeling of wildland fire phenomenology, this author's speculations on the motivations of actions related to fires in manmade structures must be understood to be those of an interested layman. Nonetheless, the following principle motivations, in order of priority, are posited and their consequences for research emphasis noted: Protect human life; minimize economic loss due to fire damage; and provide the public with adequate fire protection service at the least practicable cost. It is understood that a constraint on pursuit of these objectives is full attention to firefighter safety. There are undoubtedly many additional motivations, the precise order of the list may be inaccurate, and the phrasing may have a foreign accent, but the objectives as stated would be widely supported by the general public.

Activities related to wildland fires are motivated by a set of ordered objectives similar to those listed above: Protect human life; protect property; minimize the combined economic costs of fire control and fire loss; and support land management objectives. Pursuit of these objectives is also constrained by consideration of firefighter safety, in spite of recent catastrophic losses of life in wildfire suppression actions in the US [14]. Support of land management objectives through fire management policy is last on this list, but clearly the largest part of wildland fire research resources is devoted to perfection of such skills. When this objective is in conflict with any other, it is invariably subordinated.

Despite similarities in broad objectives, research supporting wildland and activities related to fires in buildings emphasize different phenomenology. The divergence can be explained by differences in their temporal and spatial scales and the frequency of situations in which the various objectives are dominant.

Research Supporting Urban Fire Concerns

When fire is detected within a structure, people may be inside, and potential escape routes may even be blocked by fire when firefighters arrive on the scene. The people within the burning structure may be in dire peril, their lives endangered by the inhalation of toxic gaseous products of pyrolysis or hot products of combustion, by exposure to heat, by collapsing structural elements, and by a host of ancillary threats. When firefighters arrive, they often promptly enter the burning structure wearing heat-resistant suits and equipped with air tanks, pulling along high pressure water hoses. They do this in residential and commercial structures to seek out and extricate any people within them. Sometimes provision of egress routes from outside the structure using special equipment saves the lives of potential fire victims. Secondarily, and in unoccupied structures, entry is made to minimize the loss of contents and damage to the structure. On rather rare occasions, direct suppression may be subordinated to concentration on preventing a developed fire from spreading to adjacent structures.

In the situation sketched, timely firefighter arrival and prompt, disciplined, professional action are the keys to successful rescue operations. Clearly time, measured in minutes, is the currency in which to evaluate the relative worth of alternatives. Research topics that spring from consideration of this scenario include enabling the prediction of such things as the chemical character and rate of generation of gaseous pyrolyzate from structural and furnishing materials, the flammability (relative ease of ignition) of such materials, the rate of fire spread along structural conduits, the rate of transport of hot gas and particulate matter within structures, the time lapse to be expected between ignition and full involvement of the room in which ignition occurs, and the thermal environment in which the firefighter must work and to which victims are exposed.

The results of such researches would find application mostly before the fact of the fire, in specifying standards of flammability, thermal stability, and pyrolyzate toxicity of structural and furnishing materials, in devising principles for the design of fire-safe structures, in setting performance standards for fire fighting equipment and protective apparatus, and in guiding the design and performance of fire detection, alarm, and in-situ suppression devices. One might infer that a desirable research endeavor would be development of a model to simulate the evolution of burning intensity and the rate of spread of fire within specific structures. Such models would find application mostly in the design and furbishing of very large structures, and their use in real time as an aid to tactical decision-making would be similarly limited. Their forensic use after the fact of a severe fire in a large structure is also a major economic motivation, as injured parties demand the placing of blame and the payment of compensation.

The cost of providing an acceptable level of fire protection in an urban setting is generally considered by the public to be one of the inevitable expenses of living in a safe and civilized community. Individual property owners do economic tradeoff analyses by comparing the cost of improving fire safety, such as installing smoke alarms, adding a sprinkler system, refinishing with less flammable materials, *etc.*, to the reduction in cost of fire insurance premiums. Fire service being one of the most highly cherished of public safety enterprises, it is usually adequately funded in urban areas. The towns and cities of the developed world can generally take pride in the level of training and equipping of their fire services.

Many urban dwellers who relocate to the wildland fringe in pursuit of a rural lifestyle may be chagrined to discover that such tradeoffs have vanished, and insurance against loss to wildfire may not even be available. Often, fire protection service is afforded by a brigade of volunteers who, though highly motivated and frequently courageous, are just as likely to be sparsely equipped and minimally trained. Costs in many such communities cannot be spread over time through borrowing by a taxing authority, so cash flow can dictate expenditure levels, and choices can be severely constrained. So far, the unique fire safety concerns of the urban - wildland interface (and of the industrial - wildland interface) have not yet generated, in many places, the necessary base to support research directed toward its specific needs.

Research Supporting Wildland Fire Concerns

The stereotypical forest or range fire is almost as likely to be started by lightning as by human activity. It often occurs in a remote and inaccessible area, and may well have burned for an hour or more before having been detected. The first firefighters to arrive may come an hour or so later, by parachute or helicopter, but most likely by pickup truck and boot leather. They arrive wearing hard-hats and flame-resistant light clothing, equipped with shovels, axes, and other hand tools. They set to work clearing away live and dead vegetation to make a fuel-free surround to contain the fire. If the fire is spreading too rapidly or burning with an intensity too great to permit containment by this initial attack crew, the crew will call for reinforcement and/or equipment support. Support may arrive in the form of additional personnel, perhaps with power saws and drip torches, pickup trucks carrying water pumps and possibly small water tanks, bulldozers or fire plows, or specially equipped trucks or tracked vehicles that can spray water or foam from one set of nozzles and deliver flaming liquid fuel from another.

Depending upon the severity of the present fire danger, the availability of resources, and the values at risk, fire fighting aircraft may be deployed. In Canada, and increasingly in other parts of the world, use is often made of specialized aircraft that can scoop water from a lake, a river, or the sea while skimming the surface and deliver it on the fire edge from low altitude. In the US, fixed wing aircraft usually drop a gum-thickened solution of diammonium phosphate or ammonium sulfate that acts as a flame retardant. This effect is achieved by promoting low-temperature pyrolysis of woody material with a lesser yield of combustible gaseous pyrolyzate.

If initial attack and follow-up reinforcement fails to contain the fire, additional resources are mobilized in increasing numbers in a series of steps much like a military operation. If the fire grows to be large enough, it will have its own team of specialists (called overhead), including radio operators, helicopter pilots, shovel sharpeners, medics, cooks, timekeepers, latrine orderlies, and fire behavior officers. The expense for the logistical tail of a large fire camp can be the dominant cost of a campaign fire, making the objective of minimizing cost plus loss often the dominant one. Campaign fires lasting several weeks, burning over tens of thousands of hectares, and costing tens of millions of dollars are not uncommon in the western US.

The research agenda springing from consideration of the wildland fire activities outlined include modeling to predict the rate of spread and growth of a fire, the intensity with which the edge of the fire burns, the distance ahead of the spreading fire to which it can be expected to "spot" (spread by igniting new fuel with firebrands), and not least, to predict the effects that the fire can be expected to have, not only on the landscape burned over but on the airshed and watershed downstream [15]. This latter objective supports not only assessment of anticipated economic loss to the fire, but its impact on the achievement of land management objectives. Prediction of spread rate and edge intensity are often key elements of fire effects prediction models. Surprisingly, perhaps the most expensive pieces of information required by wildland fire spread and growth models are adequate descriptions of the fuels, their abundance and condition, and the terrain upon which they exist.

Results of wildland fire research supporting these objectives find use in formulating land management plans and objectives, in planning and staffing fire control organizations, in assessing fire danger levels, in planning and executing prescribed burning operations, and in formulating strategy and planning tactics of fire control operations on campaign fires.

FIRES AT THE URBAN-WILDLAND INTERFACE

In those instances when wildland fires threaten human lives other than those of firefighters, often the situation is that of a large fire of high intensity approaching occupied structures within or at the edge of a wildland area. There is frequently much advance warning of the fire's approach, allowing residents time to evacuate or to prepare suitable shelter in which to endure passage of the fire. Some people will choose not to flee to safety but will attempt to protect their residences from incineration. In so doing they may be forced to seek shelter within the structure at the last minute, when it has been set alight by burning embers raining down ahead of the approaching wildfire. If they are fortunate, they may not only survive inside until the wildland fire has passed over, but also be able to extinguish the burning residence. The decision to flee or to defend the home is a stressful and critical decision forced upon people almost always unprepared to make the most rational choice [16].

Urban firefighters dispatched to this scene face the frustration of being trained and equipped to fight the wrong fire. With a high pressure water hose one can surely extinguish burning grass, shrubs, and even small trees. But only if the fire is within the range of the hose spray, and a long hose lay is vulnerable itself to being burned over. And if one is within hose range of an advancing crown fire, the only intelligent action is to drop the hose and flee. There will seldom exist the luxury of assigning a water-pumping tanker truck with crew to each threatened residence. Yet to do anything less is often to do the equivalent of emergency medical triage, selecting in advance which structures are to be defended adequately and which are to be left undefended. When the firefighters arrive, there are probably no people within burning structures awaiting rescue. But there may be hysterical people dashing about in a rain of embers, undertaking ineffectual fire suppression actions and placing themselves in jeopardy.

When wildland firefighters are cast in the role of protecting life and property in immediate danger, they also often sense a lack of training and equipment to perform the tasks they face. Wildland fire suppression teams (at least those employed seasonally in the US) are instructed not to enter any burning structure except in extreme emergency, to rescue someone about to perish inside. Their protective garments are not suitable for this task, they usually have no breathing apparatus, and often their only water hose is attached to a manually pumped backpack water bladder. They are accustomed to working with hand tools and power saws to clear fuel from a line surrounding a spreading fire. They long to see not pumper trucks but bulldozers in the residential driveways. Calling in air support can create its own form of disaster. Air-delivered water dropped at too low an altitude can flatten the structure being defended; from too high it is ineffective. And gum-thickened flame retardant dyes red everything it lands upon, and promptly rusts any metal with which it comes in contact.

Whenever practicable, fuel reduction is achieved by setting afire the fuel between a control line and the approaching fire. This "backfire" technique is immensely effective but not foolproof. Improper timing or an uncooperative wind can turn a backfire from an ally to an enemy. For example, a backfire may be started below a control line on the windward brow of a ridge, intended to back into an approaching wildfire. But if started too early, it may send a burning seed cone or piece of rotting wood rolling downhill, to start a fire that will have a sufficient run of unburned fuel to successfully challenge or spot over the control line. Starting the backfire too late will not reduce sufficiently the intensity of the approaching fire, and the line will again be ineffective. And firing against a control line while it is being constructed may be disastrous if a wind shift pushes the backfire ahead of the construction crew.

But in many instances, residences and even whole towns have been saved from being burned over by severe wildfires through well coordinated and properly timed backfire operations. Disciplined, professional, urban firefighters, led by a chief with considerable wildland fire experience, were credited with having saved an entire community from incineration in northern California last summer, by executing a coordinated and precisely timed backfiring operation. This was achieved in spite of the fact that many of the firefighters had never fought a wildfire nor been trained in wildfire suppression.

In such a situation, controlling human behavior is the key to saving lives, and coordination of fire fighting activity the key to minimizing risk and property loss. These elements of fire safety are not ordinarily subjects for research by physical scientists. Tractable research topics motivated by considering this scenario include modeling to predict the rate of spread of the wildland fire, modeling the distance downwind to which it can be expected to cast burning embers of consequential size, and modeling ignition of structural components such as roofing and siding by firebrands and by radiation from an approaching wildland fire. Creating such predictive models from first principles would lead immediately to study of very complex fundamental processes such as heat transfer and fluid mechanics in the flaming zone of a fire in wildland fuels, interaction of the wind field with the fire, aerodynamics of burning embers in the fire plume and downstream wind field, etc. At present it is the accumulation of experience and reliance on rules of thumb that guide most tactical planning in these situations.

While human ingenuity and heroism have repeatedly sufficed to avert tragedy, prefire reduction of hazardous fuel accumulations, use of fire-resistant construction materials (especially roofing), prepositioning of rudimentary fire fighting supplies and equipment, and enforcement of common sense rules in storing flammable materials could lessen both the need for heroism and insurance rates. Models are needed to guide and evaluate such hazard-reduction operations. And training to broaden the areas of competence of firefighters cannot be overlooked as a means of reducing losses to fires at the urban-wildland interface. Models are needed to capture, codify, and reconcile wisdom gained through experience so it can be shared and used to train inexperienced firefighters.

As mentioned above, models to predict the spread and growth of wildland fires have been developed, as have models for potential spotting distances from spreading and stationary fires [17,18]. But these models were not motivated by the improvement of fire safety in an urban - wildland interface setting, and their use in that role may reveal serious deficiencies. Some empirical evidence will be accumulated on the radiation intensity from crown fires, and it is planned that some structural materials will be exposed to that severe heat transfer environment under test conditions in Canada in the summer of 1997 [19].

The pace of such research is slow because it does not support the highest priorities of the sponsoring agencies. Because of limited resources it is important that real opportunities for measurements not be neglected and that necessary and sufficient measurements be enabled before the fact. In other words we must not only do the right things, we must do things right. It is in such endeavors that this author sees the best immediate opportunities for productive collaboration between the wildland and urban fire research communities. And, although not a specialist in either urban or wildland fire fighting technology, the author is convinced that there exist opportunities for the development of devices especially for the purpose of fighting fire at the urban-wildland interface. Perhaps the burgeoning market will entice private sector development of such technology. But some government sponsored research and development activity would surely be welcome as well.

TOPICS ADDRESSED IN WILDLAND FIRE RESEARCH

In US federal funding of wildland fire research, and perhaps in other countries as well, fire behavior and fire effects as subject matter compete for funding support. Because land managers are usually concerned more directly with the effects of a fire than with its behavior, because relatively rudimentary behavior prediction can be made to suffice in supporting fire control activities, and because process-connection models are incredibly complex and of unproved worth, most research has been of an empirical nature and has addressed fire effects. The need to bring forth usable results in a timely fashion has led to reliance on empiricism in predictive phenomenological models as well. This trait is understandable also in light of the broad range of responses of free-burning fires to wind and slope as well as to the unbounded variability in type, quantity, arrangement, and condition of its fuels.

Smoldering fire: Little work has been sponsored by wildland fire research agencies, but there is an abundant literature on behavior that seems comprehensive in scope. Fire effects in (most) forests and sites with organic mantles at least 1 cm in depth are dominated by smoldering. Smoldering fire extinction in the terminal phase of a fire control operation is often one of the most expensive. Rates of spread are on the order of 1 cm / h in the absence of wind.

Surface fire: Most research work deals with this, the most common form of wildland fire. Theoretical models abound, some of which are even realistic, but most demand data not readily available for field use. And many "one-time" modeling attempts have worked only the first time. Much theoretical work has focused on radiation as the controlling heat transfer mechanism that fixes the rate of spread. [6,20-24]. The fuel-specific empirical models developed in Canada and Australia are the easiest to use and seem to be quite adequate for their intended purposes. Semi-empirical US and Australian models are more flexible, thus perhaps better suited to planning applications, but they tend to be data intensive. Rates of spread range from the order of 0.1 m / min to a few hundred m / min.

Flame structure modeling: Much of this work dates from long ago, and ranges from strictly empirical [25] to correlations based on dimensional analyses [26], semi-empirical models [27], theoretical models [28], to software packages implementing computational fluid dynamics of reacting flows. Knowledge of the input fire edge intensity (the most common independent variable) and of the wind field acting on the flame structure probably dominate the uncertainty of predictions. The wind-blown linear flame -- even without any slope effect -- has been ignored in the combustion literature, as this geometry is hardly ever used industrially. Seabed sewage discharge from a perforated pipe in a cross current is the only fluid mechanical equivalent process found in the engineering literature so far.

Torching, crowning, transition to / from crown fire: Very little theoretical work has been done in the West. Theoretical work by Russian analysts [29] is essentially untested as yet. Canadian fire research pioneer C. E. Van Wagner [30] has developed and tested semi-empirical relationships tied to the Canadian forest fire behavior prediction system [31].

Crown fire: More theoretical work in this area has been done recently. Theoretical models have been published recently [29] or are still in development [32] and are untested. They demand data that must be stereotyped to be useful. The Canadian empirical models should work well for any boreal conifer forests; the current US regional model [33] simply multiplies the surface fire spread rate by 3.34 and remains largely untested.

Fire spotting: This is largely a neglected area but an extremely important one. Empirical work on the probability of ignition - vs - fuel moisture is being used operationally in the US [34] but not being systematically tested. Mainly theoretical models [17,18] are also being used to predict the maximum spotting range to be expected from various fire situations. These, too, have had little testing. Stochastic spotting events have been accommodated in fire growth simulation models [35].

Fuel migration: Burning seed cones, stumps, and even whole tree boles can become dislodged and travel downslope, sometimes for great distances and at high speed. This mode of fire edge movement is often more rapid downslope than is upslope spread. No work is being done on this phenomenon of which I am aware, and it is often neglected in mathematical simulations of fire growth. Experienced firefighters know better, of course.

Fire growth modeling: This topic has become popular with mathematically inclined analysts recently, driven partly by desire to generate simulations of fire growth on landscape scale for "what if" planning, and for the more glamorous role of campaign fire growth projection. These are mathematically complex models [35] that may include spotting but usually ignore migrating fuel. They are now being used in campaign fire strategic planning. Fire perimeter location updates by real time aerial observations using GPS and rapid access to GIS based fuel and terrain data should make these models quite valuable in this role. Although stochastic spread and growth models occasionally have been proposed, more physically based models seem to have found broader acceptance in the community of practitioners.

Variation of fire spread rate due to wind speed and direction changes: Steady wind in a constant direction is unusual, even for short durations. Most wildland fire deaths occur in "light, flashy" fuels, due to unanticipated shifts in wind direction and/or changes in speed [36]. In spite of this motivation, little theoretical work has been done on this problem [37]. Field observations of forward rates of spread of grass fires in shifting winds recently have been correlated to apparent fire front width [38] without a proposed causal connection.

Wind field / fire interaction: This topic has recently become a popular one with supercomputer users, especially from the ranks of mesoscale meteorologists. It would appear at first glance that both engineering and meteorological CFD models might encompass this phenomenology. But engineering models were crafted to simulate industrial processes that are reaction rate driven and controlled by manipulable boundary conditions, so they generally deal with flow structures having much shorter time scales and much smaller physical scales. And mesoscale meteorological models were developed to describe slower, larger scale phenomena than free-burning fire processes that depend upon the wind field, such as rapid responses to shifts in wind direction. The biggest obstacle to progress in this field may be uncertainty in what it is that the models must seek to describe. As of now, unknown sequences of events give rise to such phenomena as the unburned crown strips documented by Haines [39] and the fire size-dependent spread rate sensitivity to wind speed documented by Cheney and Gould [38]. How would the modeler recognize success without a clear picture of the phenomenology involved?

ACCESSING AND USING WILDLAND FIRE RESEARCH

The foregoing discussions address the motivations underlying, and general topics addressed by wildland fire research, followed by a brief summary of phenomenology considered in these endeavors. I shall not try here to provide a classical survey of this literature, but instead will point to the comprehensive bibliography available in machine-readable form from the International Association of Wildland Fire, and commend its use to all who seek a current, comprehensive source. This resource should do much to alleviate the frustrations of searching in unfamiliar places for unlikely literature. For example, I would speculate that few chemists are aware of extensive experimental work on the thermochemistry of natural fuels to be found in Forest Science [40-42]. And few engineering heat transfer specialists know of the measurements of the emissive powers of flames from wind tunnel fires in natural fuels reported at the 1993 conference on Fire and Forest Meteorology [43].

In conclusion, I find it incumbent upon me, as an apologist for wildland fire research, to offer some guidance in assessing the uneven quality of the scattered literature in this field. Because of the clutter of technical jargon, imprecise descriptive prose, and shorthand references to a body of folk knowledge, the investigator first encountering this literature may find that it is not worth the effort to make a determination whether or not the material should be taken as presented or whether there are important qualifications hidden in the title, references, or cryptic content. In an attempt to further the state of the art of wildland fire science by involving a broader community of researchers, I offer the following as a rough guide for the uninitiated to quality assessment of wildland fire research literature. I hope that in offering these snippets I will offend as few of my colleagues as possible and entice as many new investigators as possible to this challenging, intriguing, and poorly funded field of research.

As mentioned above, government laboratories and agencies work on problems dealing with wildland fire behavior and effects. Although it is not fashionable to champion bureaucratic agencies and their monopolistic claims on research funding, these institutions have, over the years, provided technical tools for use in assessing the severity of wildland fire danger, in predicting the behavior of fires, and abundant information on the effects of wildland fires. Usually these tools have been made available not only to fire and land management professionals but to the community at large, from scholars of esoterica to rural volunteer firefighters. And when they are made so available, they are offered as standardized training courses for practitioners, as user-friendly computer programs, as graphical computation aids, and as sets of simple equations. In all cases the materials are buttressed by users' manuals and extensive documentation. These packets of knowledge are also accompanied by aids for the interpretation of derived results and appropriate cautions against misapplication of the methods. While the predictions made by these procedures can suffer significant error, the user is apprised of the probable levels of uncertainty in manuals and accompanying documentation.

In this context I will mention specifically the USDA Forest Service fire behavior prediction system that consists of several personal computer algorithm sets known collectively as the BEHAVE system, the Canadian Forest Service's fire behavior prediction system (tied to the Canadian forest fire danger rating system) and the systems published by CSIRO for Australian fuels. The experienced user can access on-line utilities such as the ACT Bushfire Fighters Newsletter which has McArthur's Fire Danger Meter software on its FIREBREAK home page {http://msowww.anu.edu.au/~barling/firebreak.html}. These systems have empirical content and rely on the judgment of the user not to misapply them; descriptive instructions and some photo series guides are available to help estimate input data. For those seeking information on the effects of wildland fires, USDA Forest Service maintains a data retrieval and literature search system on line at the Intermountain Fire Sciences Laboratory in Missoula Montana. This site can be accessed by Internet connection through the USDA Forest Service home page {http://www.fs.fed.us}or directly by {http://www.fs.fed.us/database/feis/welcome.htm}. I am sure there is at least a similar system in Australia, but I have no reference to it at this writing.

In short, if the needs you have for wildland fire predictions can be satisfied at this level, then the use of these government-sponsored practitioners' aids is recommended. If your needs are of a more quantitative or theoretical nature, you may have to consult the recent literature in the field. To those who must venture into this realm, the following remarks are directed. Have a care if you sense that:

1. <u>The work seems to be in the wrong journal.</u> When a paper dealing extensively with an arcane specialty such as computational fluid dynamics, complex heat transfer processes, or esoteric mathematical or statistical manipulations appears in an application-oriented "trade journal" style publication, it is at once apparent that the readership will not appreciate the work. That is, if the readers pay any attention at all to the article, it is to be dazzled by the spectacle rather than to be informed by the results of the work. The work may appear in the wrong journal because it would not be accepted by a journal specializing in the specialized subject area. In a perfect world it would appear as a note in a technical journal, with a synopsis of its practical applications in a layman's presentation in the appropriate trade journal.

2. <u>The motivation for the work is confusing, contradictory, or nonexistent.</u> In a brief communication or note, motivation can be communicated by citing references to which it should be appended. But in presenting new developments or extending an area of research, it is incumbent upon the authors to spell out in rather a complete way how their work fits into the context of the state of knowledge and/or practice in the field. This is not to say that each paper should be a survey article, but it should be clear to the reader that the authors understand the present state of knowledge and are offering specific advances that fill voids or

improve current practice. When such context-specific motivation is lacking in a otherwise substantial corpus of work, it may represent no contribution to the body of knowledge. Except where space constraints are severe, the recitation of a series of citations is an inadequate statement of motivation.

3. Limitations on applicability are not spelled out in practical terms. If the authors make no mention of limitations on the applicability of the work other than by way of the qualifying of assumptions invoked, then it may be that they do not recognize the limitations. This, in itself, clearly does not mean that the work is inconsequential, especially if it appears in a specialized journal and that specialty comprises the substance of the article. But if it deals with a topic the journal readership would find unfamiliar and if practical applications are cited as the motivation for the work, then the reader should beware. This circumstance sometimes arises when specialists are consulted in dealing with some aspect of a complex problem and they mistakenly conclude that, by resolving the questions they have been asked to address, they have solved the problem that motivated the research program to which they have made a necessary but not a sufficient contribution.

4. Undefined symbols and mathematics without explanation. The appearance of undefined symbols in equations is almost always an indication of inadequate review. Except in cases where certain symbols are reserved by convention to represent certain quantities, or where the notation of a reference is adopted by citation, the appearance of even a few undefined symbols in an article means the reviewers and editors were asleep on the job. The same can be said for mathematical derivations consisting of sequences of equations with no discussion of the physical meanings of the relationships displayed or worse, the unexplained appearance of a result with no clue as to how it was obtained. When the reader encounters such content he can almost be sure that the paper was inadequately screened before publication.

5. Research from China and the former Soviet Union? Finally, I must address the increasing accessibility of research in this field by scientists from China and the former Soviet Union. As the world knows, the academic research traditions of Russia and China are rich in scholarship, mathematical elegance, and conciseness of text. Works by our Soviet colleagues are usually framed in maximal generality, often including effects and influences that, as a matter of style, their Western counterparts might dismiss for simplicity. Russian scientific works are also noted for specialization, an attribute perhaps the result of the compartmentalization of most technical work under the centralist Communist hierarchy.

Recently Western researchers have had increased access to the abundant literature on wildland fires published in the former Soviet Union. International conferences in Krasnoyarsk in 1994, Tomsk in 1995, Shushenskoye in 1996, and planned for Irkutsk in 1997 underscore the determination of the Russian fire research cadre to become a part of the world community of their technical peers. While I am aware of many research works by our Russian colleagues and am intimately familiar with a few, I can offer no general assessment of the value of these works to this audience. To the Western community of wildland fire researchers I have suggested that these works be studied for the modeling insights and the computational approaches they offer. As for the quality of results from application of the models, I can only note that there has been as yet insufficient testing to reach any conclusions in this regard.

The vast and varied nation of China has a substantial history of wildland fire experience which we might hope to share more fully in the near future. While illiteracy in the Chinese language poses a barrier that frustrates most Western investigators, very many Chinese scholars are fluent in the languages of the West. And, based upon the increasing frequency and perceptiveness of the personal inquiry communications that I receive from Chinese scientists and students on the topic of wildland fire research, I can deduce that our colleagues in China are much better informed about current Western research in this field than we are about their work. I am hopeful that this dialogue will continue and broaden to our mutual benefit.

REFERENCES

1. Brown, A. A., and K. P. Davis, Forest fire control and use, 2nd edn., McGraw-Hill, New York, 1973.

2. Luke, R. H., and A. G. McArthur, Bushfires in Australia, Australian Govt. Publ. Service, Canberra ACT, 359 pp, 1978.

3. Chandler, C., P. Cheney, P. Thomas, L. Trabaud, and D. Williams, Fire in forestry v. 1. Forest fire behavior and effects, Wiley-Interscience, 450 pp (ISBN 0-471-87442-6), 1983.

4. Chandler, C., P. Cheney, P. Thomas, L. Trabaud, and D. Williams, Fire in forestry v. 2. Forest fire management and organization, Wiley-Interscience, 298 pp (ISBN 0-471-87447-7), 1983

5. Pyne, S. J., P. L. Andrews, and R. D. Laven, Introduction to wildland fire, 2nd edn., John Wiley & Sons, New York, 769 pp (ISBN 0-471-54914-4), 1996. See especially Ch. 11.

6. Emmons, H. W. "Fire in the forest." Fire Research Abstracts and Reviews, 5,3:163-78, 1964.

7. Williams, F. A., "Urban and wildland fire phenomenology", Progress in Energy and Combustion Science, 8:317-354, 1982.

8. Weber, R. O., "Modelling fire spread through fuel beds", Progress in Energy and Combustion Science, 17:67-82, 1991.

9. Albini, F. A., "Wildland fires", American Scientist, 72:590-597, 1984.

10. Albini, F. A., "Dynamics and modeling of vegetation fires: Observations", in Fire in the environment: The ecological, atmospheric, and climatic importance of vegetation fires, Ed. P. J. Crutzen and J. G. Goldammer, pp 39-52. Dahlem Konferenzen ES 13. John Wiley & Sons, Chichester, (ISBN 0-471--93604-9), 1993.

11. Greenlee, J. M., "Large fire in New Jersey forces evacuations", Wildfire 4,2:13-14,1995.

12. Wichman, I. S., and A. Atreya, "A simplified model for the pyrolysis of charring materials", Combustion and Flame 68:231-247, 1987.

13. Albini, F. A., and E. D. Reinhardt, "Modeling ignition and burning rate of large woody natural fuels", International Journal of Wildland Fire 5,2:81-91, 1995.

14. Putnam, T., "The collapse of decisionmaking", Wildfire 4,2:40-45, 1995.

15. Albini, F. A., and J. K. Brown, "Mathematical modeling and predicting wildland fire effects", Combustion, explosions, and shock waves [Transl. Fizika Goreniya i Zvryva] No. 5: In press, 1996.

16. International Association of Wildland Fire (IAWF), "Focus", Wildfire 4,2:22-39, 1995.

17. Albini, F. A., "Spot fire distance from isolated sources -- extensions of a predictive model", Research Note INT-309. Ogden UT: USDA Forest Service Intermountain Research Station. 9 pp., 1981.

18. Albini, F. A., "Potential spotting distance from wind-driven surface fires", Research Paper INT-309. Ogden UT: USDA Forest Service Intermountain Research Station. 27 pp, 1983.

19. Cohen, J., USDA Forest Service Intermountain Fire Sciences Laboratory, Missoula MT. Private communication October 1996.

20. Hottel, H. C., G. C. Williams, and F. R. Steward, "Modeling of fire spread through a fuel bed", Proc. Tenth symposium (international) on combustion, 997-1009. The Combustion Institute, Pittsburgh, 1964.

21. Thomas, P. H., "Some aspects of the growth and spread of fire in the open", Forestry 40:139-164, 1967.

22. Telitsin, H. P., "Flame radiation as a mechanism for of fire spread in forests", in Heat transfer in flames, ed. N. H. Afgan and J. M. Beer, 441-449, John Wiley and Sons, New York., 501 pp, 1974.

23. Albini, F. A., "Wildland fire spread by radiation -- a model including fuel cooling by natural convection", Combustion Science and Technology 45:101-113, 1986.

24. Carrier, G. F., F. E. Fendell, and M. F. Wolff, "Wind-aided firespread across arrays of discrete fuel elements. I. Theory", Combustion Science and Technology 75:31-51, 1991.

25. Byram, G. M. in Brown and Davis [1], p. 90, 1959.

26. Thomas, P. H., "The size of flames from natural fires". Proc. Ninth symposium (international) on combustion, 844-858. The Combustion Institute, Pittsburgh, 1963.

27. Albini, F. A., "A model for the wind-blown flame from a line fire", Combustion and Flame 43:155-174, 1981.

28. Steward, F. R., "Linear flame heights for various fuels", Combustion and Flame 8:171-178, 1964.

29. Grishin, A. M., Matematicheskoye modelinrovaniye lesnik pozharov i novi sposobi borbi s nimi [Mathematical modeling of forest fires and new methods of fighting them] Nauka, Novosibirsk. 408 pp., 1992.

30. Van Wagner, C. E., "Prediction of crown fire behavior in two stands of jack pine", Canadian Journal of Forest Research 23:442-449, 1993.

31. Forestry Canada Fire Danger Group, Development and structure of the Canadian forest fire behavior prediction system, Forestry Canada, Science and Sustainable Development Directorate, Ottawa, ON. Information Report ST-X-3, 64 pp., 1992.

32. Albini, F. A., "Iterative solution of the radiation transport equations governing spread of fire in wildland fuel", Combustion, explosions, and shock waves [Transl. Fizika Goreniya i Zvryva] No. 5: In press, 1996.

33. Rothermel, R. C., "Predicting the behavior and size of crown fires in the northern rocky mountains", Research Paper INT-438. Ogden, UT: USDA Forest Service, Intermountain Research Station. 46 pp., 1991.

34. Andrews, P. L., "BEHAVE: fire behavior prediction and fuel modeling system: BURN subsystem, Part 1." General Technical Report INT-194. Ogden, UT: USDA Forest Service, Intermountain Research Station., 1986.

35. Finney, M. A. "Modeling the spread and behavior of prescribed natural fires", Proc. 12th conference on fire and forest meteorology pp 138-143. Society of American Foresters publication 94-02 (ISBN 0 - 939970 - 60 - 0), 1994.

36. Wilson, C. C., "Fatal and near-fatal forest fires, the common denominators", International Fire Chief 43,9:9-15, 1977.

37. Albini, F. A., "The variability of wind-aided free-burning fires", Combustion Science and Technology 31:303-311, 1983.

38. Cheney, N. P., and J. S. Gould, "Fire growth in grassland fuels", International Journal of Wildland Fire 5,4:237-247, 1995.

39. Haines, D. A., "Horizontal roll vortices and crown fires", Journal of Applied Meteorology 21:51-63, 1982.

40. Susott, R. A., "Thermal behavior of conifer needle extractives", Forest Science 26,3:347-360, 1980.

41. Susott, R. A., "Characterization of the thermal properties of forest fuels by combustible gas analysis", Forest Science 28,2:404-420, 1982.

42. Susott, R. A., "Differential scanning calorimetry of forest fuels", Forest Science 28,4:839-851, 1982.

43. Butler, B. W, ".Experimental measurements of radiant heat fluxes from simulated wildfire flames", Proc. 12th conference on fire and forest meteorology pp 104-111 Society of American Foresters publication 94-02 (ISBN 0 - 939970 - 60 - 0), 1994