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Wildland–urban interface fire behaviour and fire modelling in live fuels

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Many of the most spectacular wildland fires are observed when live fuel complexes become involved in the fire. When these fires occur in the wildland–urban interface (WUI) such as Melbourne, Australia (2009), the southern Peloponnese in Greece (2007), southern California in the United States (2007), and Portugal (2005), major destruction and loss of life can occur. Fires are observed in live fuel types on all continents except for Antarctica. In Australia, New Zealand, and Tasmania, the primary live fuels include eucalyptus forests and woodlands and heathlands (Chandler *et al*. 1983, 1991; Cary *et al*. 2003). In Mediterranean regions of the world, shrubs are the primary live fuel complex and are known by various names including chaparral, mattoral, garrigue, and fynbos (Moreno and Oechel 1994). In the northern hemisphere coniferous forests on all continents can experience crown fires – particularly forests in the boreal regions. Other fuel complexes contain a mixture of living and dead fuels such as the palmetto-gallberry fuel type of the south-eastern United States and gorse and heathland fuel types of central and northern Europe. The last major category of live fuels includes grasses, rushes, and sedges which grow in wetland areas and can support combustion over standing water. The movement of people from urban areas into rural areas as well as the reversion of agricultural areas into wildland areas has expanded the WUI resulting in increased fire risk and a need to change the focus of 'traditional' wildland fire behaviour research.

Although it may indeed be arguable that fire behaviour in live fuels is at least as important a research topic as fire behaviour in dead fuels, research focus on these fuels has been limited since the inception of fire research in most countries. This is due in part to the fact that fire spread in these horizontally and vertically heterogeneous fuel beds is a complex process that is influenced by many variables. The pioneering scientists who began fire research in the 1920s and 1930s focussed on problems that were tractable with the knowledge and tools that were available at the time (i.e. Gisborne 1936). As a result, most of the work was focussed on relatively homogeneous, shallow fuel beds of dead fuels such as cured grass and leaf litter (Rothermel 1972). Fire spread problems were typically focussed in forests which were commercially valuable since the early fire research was conducted by scientists working in forest management organisations. This early work was both experimental and empirical in nature and generally focussed on forest protection. Perhaps the one exception to the empirical modelling was the work of Fons (1940) who produced a fire spread model based on heat transfer theory. This early work yielded results that form the basis of fire spread prediction and fire danger assessment worldwide. The reader interested in understanding the cultural and historical aspects of wildland fire from an international perspective is referred to the 'Cycle of Fire' series of books written by historian Stephen J. Pyne.

In contrast, in the United States, fire behaviour research in live fuels has not received the attention that it may warrant. Weise *et al*. (2005) provided a brief synopsis of the live fuel fire behaviour research previously conducted in the USA. The past decade has seen an increased emphasis on measuring and modelling fire behaviour in live fuels. Improved instrumentation and computing resources have made possible better measurement of fire phenomena and numerical solution of the conservation equations governing fire behaviour. As a result, there has been an explosion of new data and models describing various aspects of fire behaviour and combustion in live fuels which also includes the use of biomass for energy. The series of International Forest Fire Research symposia held quadrennially in Portugal have provided international opportunities for the dissemination of this new research.

Scientists began talking about WUI fires in the early 1970s and the loss of homes to wildfires was a familiar occurrence in southern California (Wilson 1962), but there was little concerted effort in the USA to tackle the complex problems until the late 1980s (Davis 1990; Sommers 2008). In contrast to the limited fire behaviour work in the WUI, there has been significant work focussed on fires in the built environment before and following the establishment of the USA Department of Commerce's Building and Fire Research Laboratory at the National Institute of Standards and Technology (NIST) (Committee on Fire Research 1969; Wright 2003). This research has provided the fundamental data and modelling that form the basis for construction codes, material selection, material testing, and numerous other aspects of building fire. Suffice it to say that the field of building fire research is well developed in many of the industrialised countries of the world.

The WUI is where these two areas of research, wildland fire and building fire, overlap. Unfortunately, the actual overlap and integration between the two research areas has seldom occurred in the United States. The 2nd Fire Behaviour and Fuels Conference held 26–30 March 2007 in Destin, FL afforded an opportunity to encourage such overlap. Two special sessions were organised to support the conference theme 'The Fire

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Table 1. Listing of presentations made in two special sessions of the 2nd Fire Behaviour and Fuels Conference, 26–30 March 2007, Destin, FL

Session	Title	Authors
Fire modelling in live fuels	Measurements of mass and temperature during ignition of fresh foliage from western wildland environments	B. M. Pickett, T. H. Fletcher, D. R. Weise
	Marginal burning in chaparral – experiments and models	S. Mahalingam
	Modelling the transition from a surface fire to a chaparral crown fire	W. Tachajapong, S. Mahalingam
	Active spreading crown fire characteristics: implications for modelling	J. D. Cohen, M. A. Finney, K. M. Yedinak
	Experiments on fire spread in discontinuous fuelbeds	M. A. Finney, J. D. Cohen, I. C. Grenfell, K. M. Yedinak
	Flame shape and convective heat transfer in deep fuel beds	K. M. Yedinak, J. D. Cohen, J. Forthofer, M. A. Finney
	FIRETEC simulations in chaparral	R. R. Linn
	A sub-grid, mixture-fraction-based thermodynamic equilibrium model for gas phase combustion in FIRETEC: development and results	M. Clark, T. H. Fletcher, R. R. Linn
	Tree burning experiments and modelling of crown fires	W. Mell, B. Butler, A. Maranghides, S. Manzello
	Spatial modelling of fire in shrublands with HFire	M. A. Moritz, P. E. Dennison, M. E. Morais
	The influence of live fuels on the Rothermel surface fire spread model	W. M. Jolly
Wildland–urban interface fire behaviour	Fire and the wildland–urban interface microenvironment	R. N. Meroney
	A review of firebrands	E. Koo, P. J. Pagni, D. R. Weise, J. P. Woycheese
	Large and bench scale laboratory firebrand experiments	S. Manzello
	Testing and classification of individual plants for fire behaviour	W. Zipperer, R. H. White
	Fire spread models applied to chaparral – a California WUI fuel type	E. Koo, P. J. Pagni, S. L. Stephens, D. R. Weise
	Ignition and flame travel on realistic building and landscape objects in changing environments	M. A. Dietenberger
	Fire spread modelling in WUI fuels	W. Mell, R. Rehm

Environment – Innovations, Management, and Policy' and scientists from the wildland and building fire research community were invited to make presentations on selected topics. A session focussed on fire modelling in live fuels included 10 presentations on ignition, marginal burning, transition to crowning, and discontinuous fuel beds as well as different modelling approaches for fire spread in live fuels (Table 1). A session on WUI fire behaviour included seven presentations on the WUI microenvironment, firebrands, landscape plant flammability, ignition and flame travel, and fire spread modelling in WUI fuels. The abstracts for all presentations in the two sessions are contained in Butler and Cook (2007) and the information contained in some presentations has been published in other outlets (Cohen *et al*. 2006; Jolly 2007; Manzello *et al*. 2007, 2008; Meroney 2007; Peterson *et al*. 2009).

In the WUI session, Prof. Meroney presented a talk based on a presentation he made at the NATO Advanced Study Institute on Flow and Transport Processes in Complex Obstructed Geometries (Meroney 2007). This presentation included information on large urban fires, various modelling methodologies that have been used to predict smoke and flame behaviour, studies examining wind flow fields around single trees, and within forest and urban canopies, fluid mechanics of fires and porous canopies, and fire whirls. The work described occurred within and external to the fire research community; the flow field and fluid mechanics have the potential to improve our ability to model fire. Koo *et al*. (in press) presented a general review of past and present work on firebrands. The review included urban and wildland fires where firebrands were a significant spread mechanism, work on firebrand properties, and description of firebrand transport models. A new model for firebrand transport was presented and preliminary results of the integration of this model into the Los Alamos FIRETEC fire spread model (Linn *et al*. 2002; Koo *et al*. 2007) were presented. Koo *et al*.'s second presentation focussed on the comparison of fire behaviour data from three prescribed burns in chaparral (Stephens *et al*. 2008) with predictions from a modified version of Pagni and Peterson's original physics-based surface fire spread model (Koo *et al*. 2005). The presentation by Manzello *et al*. at the National Institute of Standards and Technology presented information on firebrand production by Douglas-fir trees burned at NIST and the ability of these firebrands to ignite fuel beds (Manzello *et al*. 2007).

The remaining three papers from the WUI session are presented in this issue. In the first article (Mell *et al*. 2010) present 'an overview of the WUI fire problem, a short review of current approaches to addressing the WUI fire problem and reducing structure ignitions, a discussion and assessment of further needs, and an overview of the ongoing work at NIST to address some of the research needs.' They note that there is currently no national consistent approach to assessing fire risk in the WUI and that the approaches used vary greatly. The work occurring at NIST that they report is focussed on providing experimental data and modelling to support the development of WFDS, a modification of NIST's Fire Dynamics Simulator to simulate WUI fire dynamics. The second article (Dietenberger 2010) presents an alternative approach to modelling fire risk in the WUI. A fire hazard calculation tool '. . .[that] account[s] for variation of flammability properties of common materials, for time changing processes of ignition and fire growth on each landscape and structural combustible object, and for the time changing wildfire exposure

from outside the parcel lot' is described. Analytical solutions of the dynamic processes of surface heating to ignition/flame travel that leads to overall fire growth are presented. One of the recommendations that fire agencies make to homeowners in the WUI is to landscape their property with low flammability vegetation. The third article from the WUI session (White and Zipperer 2010) presents a review of plant flammability. The paper 'review[s] the different components of flammability as they apply to plants, look[s] at different techniques to measure these components, and discuss[es] advantages and disadvantages of each technique, specifically oxygen consumption calorimetry because of its application for testing flammability of whole plants.'

The live fuel session contained a total of eleven presentations (Table 1) that were primarily focussed on fire spread in shrub fuels and in conifer crowns. Cohen *et al*. presented thoughts on the modelling of crown fires based on different characteristics of crown fires in conifers. This presentation was also made at the Fifth International Conference on Forest Fire Research in Portugal (Cohen *et al*. 2006). Mahalingam *et al*. made two presentations examining two transitions in fire behaviour in chaparral fuel types – the transition from no spread to spread in fuel beds composed of only live material and the transition from a spreading surface fire in dead fuels to fire spread in elevated fuel beds of live material. Experimental data and physical modelling illustrated the importance of convective heat transfer in these two transitions in fire behaviour. The content from these presentations has been published elsewhere (Weise *et al*. 2005; Zhou *et al*. 2007; Tachajapong *et al*. 2009). Mell *et al*. presented results of the integration of experiments examining the burning of individual Douglas-fir trees at NIST with information from the International Crown Fire Modelling Experiment (Stocks *et al*. 2004). Moritz and colleagues presented HFire, a 2-D implementation of the Rothermel (1972) spread model, and applied it to the spread of a wildfire that occurred in chaparral. A computational comparison with a version of the FARSITE implementation (Finney 1998) of the Rothermel model was presented. These and other published results related to HFire can be found in Peterson *et al*. (2009) and Clark *et al*. (2008). Jolly presented an analysis of how the information on live fuels is included in the Rothermel model and how changes in live fuel moisture content can influence the model outputs. This information can be found in Jolly (2007). The remaining five presentations from the live fuel session are contained in this special issue.

The paper by Clark *et al*. (2010) describes an enhancement to the FIRETEC computational fluid dynamics model of fire spread. A modelling approach used in the field of coal combustion is incorporated into FIRETEC and compared with the earlier implementations of sub-grid combustion models. Predictions of the model for grass, chaparral, and ponderosa pine (*Pinus ponderosa* C. Lawson) fuel beds are presented. In a second paper about the FIRETEC model, Linn *et al*. (2010) examine the effects of slope and fuel structure on predicted rate of spread. The same fuel bed types used by Clark *et al*. (2010) were draped on flat terrain and an idealised hill. Predicted fuel temperature, convective, and radiative fluxes were examined. Interesting interactive effects of fuel type and terrain are reported. The third paper (Pickett *et al*. 2010) presents results of an experiment examining the combustion characteristics of single particles of live fuels from the south-eastern, south-western, and intermountain regions of the United States. Internal fuel particle temperatures in excess of 140°C challenge the classical fuel particle-heating model utilised in many fire spread models. The remaining two papers in this issue examine different aspects of a novel set of laboratory experiments performed by Cohen and coworkers. In Finney *et al*. (2010), a set of laboratory experiments using fine dead fuels arranged in deep, discontinuous, vertical columns to examine threshold fire spread behaviour is presented. The effects of gap structure, depth, and slope were examined. Analysis of high-speed photography of the flames enabled examination of intermittent *v.* continuous flame bathing of the fuel particles. The final paper in this issue by Yedinak *et al*. (2010) continues the examination of the flame properties within deep, discontinuous fuel beds and presents a laminar flame model to examine convective heat transfer in these fuel beds. Comparison of the model with the flame data suggests that the flame exhibits laminar, transitional, and turbulent characteristics as the fuel depth increases.

The papers contained in this special issue present state of the science information and approaches to modelling fire spread in the WUI and in live fuels as they exist currently in the United States. The modelling approaches used range from empirical to numerical to analytical. The scale of modelling ranges from single fuel particles to fire spread prediction of an entire fire perimeter and medium-range transport of firebrands. The papers are the outcome of an increased effort on the part of fire behaviour scientists to understand the intricacies of fire spread in complex fuel beds and to integrate research efforts to help to solve the challenge to fire management posed by these fuels in many parts of the world. In many of these papers, the importance of convection as a heat transfer mechanism in wildland fuels is highlighted. This is a significant advancement over earlier modelling efforts in which radiative heat transfer was viewed as the dominant mechanism. As with everything related to fire behaviour, scale is important because it determines the relative importance of the some 29 dimensionless groups of variables that can influence combustion (Williams 1969, 2008).

These papers are not the beginning of the dialogue, but are a continuation of a dialogue that has been occurring for the past decade. Although the specific applications of the models are currently focussed on the fire problem within the United States, the models and modelling approaches are applicable to the problem internationally. It is our hope that presentation of this group of papers to the international fire modelling community will further stimulate the cross-fertilisation of ideas and collaborative approaches to the complex problems of fire spread in the WUI and in live fuels.

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