FIRESCIENCE.GOV
Research Supporting Sound Decisions

Project Title: Developing a post-processor to link the Forest Vegetation Simulator (FVS) and the Fuel Characteristic Classification System (FCCS)

Final Report to the Joint Fire Science Program

JFSP Project ID 12-1-02-35

July 31, 2015

PRINCIPAL INVESTIGATOR:
Morris C. Johnson
USDA Forest Service, Pacific Northwest Research Station
Fire and Environmental Research Applications (FERA) team
Pacific Wildland Fire Sciences Laboratory
400 North 34th Street, Suite 201, Seattle, WA 98103
Telephone: (206) 732-7832 Facsimile: (206) 732-7801
E-mail: mcjohnson@fs.fed.us

COOPERATORS:
Sarah Beukema- ESSA, Vancouver, BC
Stephanie Rebain-USFS, Forest Management Service Center, Fort Collins, CO
Paige Eagle – University of Washington, Seattle, WA
Kjell Swedin- University of Washington, Seattle, WA
Maria Petrova-University of Washington, Seattle, WA
Susan Prichard, University of Washington, Seattle, WA

Abstract

In this project, we developed a Forest Vegetation Simulator (FVS, JFSP Project #) post-processor (FVS2FCCS) to convert FVS simulated treelist and surface fuel data into Fuel Characteristics Classification System (FCCS, *JFSP Project #98-1-1-06*) fuelbed format (.xml) that can be read and processed by the FCCS to create estimates of surface fire behavior, including reaction intensity (Btu ft^{-2} min^{-1} or kJ m^2), rate-of-spread (ft min^{-1} or m min^{-1}), and flame length (ft or m). Post-processors are programs that extend FVS modeling, reporting, and display capabilities. Our post-processor allows forest and resource managers to combine FVS simulated fuelbed characteristics (tree canopy data, dead woody fuel loadings) with information about shrubs and herbaceous stand components to build FCCS fuelbeds. This tool allows managers to conduct fire hazard assessments and explore "How do changes in shrub and herbaceous vegetation affect potential fire behavior and fire effects?" Managers can compare potential reaction intensity, rate-of-spread, and flame lengths to estimates of these metrics that are generated by other fire behavior models (e.g., BEHAVE).

Background and Purpose

In dry forest types, resource managers develop and evaluate fuel treatments (thinning, prescribed fire, pile-and-burn) that are designed to reduce decades of fuel accumulation (surface fuel loadings, tree densities), potential crown fire hazard and wildfire behavior and severity (Graham et al 1999; Peterson et al. 2005; Johnson et al. 2011). To test treatment efficacy, resource managers rely solely on an array of simulation tools (e.g., BEHAVE (Andrews 1986), Fire Area Simulator (Finney 1988), Nexus (Scott 1999), and the Fire and Fuels Extension to the Forest Vegetation Simulator (Reinhardt and Crookston 2003) to estimate change in potential fire behavior and fire hazard using area specific weather and fuel moisture conditions (Reinhardt and Crookston 2003). Current simulation models do not calculate treatment effects using actual fuel inventory data (e.g., measured woody, shrub, and herbaceous fuel composition, arrangement, and loading). Instead, these models utilize a set of stylized fuel models (Albini 1976, Anderson 1982, Scott and Burgan 2005) as fuel input to predict potential fire behavior. Stylized fuel models are a set of fuel parameters intended to characterize a surface fuelbed that will yield an expected measure of fire behavior (Noonan-Wright et al. 2013). Stylized models do not quantify the complexity and variability of fuels in natural forest conditions (Sandberg et al. 2001), nor do they adequately represent the shrub or herbaceous vegetation fuel components, which can be major contributors to fire behavior. However, emerging and existing modeling systems can be integrated to more closely evaluate potential fire behavior by including all components within a fuelbed that has the capacity to burn (Sandberg et al. 2001). In this project, we integrated a commonly used simulation model, Forest Vegetation Simulation (Dixon 2011), and a new fuel characterization and fire behavior prediction system, the Fuel Characteristic Classification System (Ottmar et al. 2007), to provide users with the opportunity to use all fuel components of a fuelbed to estimate potential fire behavior (Ottmar et al. 2007). This tool, FVS2FCCS), gives managers an alternative modeling system for estimating potential fire behavior, specifically estimates of reaction intensity (Btu ft^{-2} min^{-1} or kJ m^2), rate-of-spread (ft min^{-1} or m min^{-1}), and flame length (ft or m).

The Forest Vegetation Simulator (FVS) has a long legacy of research and development, and is the standard forest development model used by foresters, silviculturists, and fire managers from various government and state agencies including the USDA Forest Service, USDI Bureau of Land Management, and USDI Bureau of Indian Affairs (Dixon 2011). FVS is an individual-tree, distance-independent, growth-and-yield model which simulates silvicultural treatments and forest-stand dynamics for many forest types found across the United States (Dixon 2011). FVS has 20 regional variants (specific tree growth, mortality, and volume equations) calibrated for major tree species within specific geographic areas (Dixon 2011). Model projections are easily customizable to simulate a wide variety of silvicultural treatments. FVS has various extensions to represent the effect of insects and root diseases: western root disease (Frankel 1998), Douglas-fir beetle impact model (Marsden et al. 1994), and mountain pine beetle (Crookston et al. 1978). Importantly, managers can import stand exam (tree list) data from national forest inventory programs such as the Forest Inventory Analysis (FIA) or the Field Sampled Vegetation (FSVeg) database.

The FVS companion program, Fire and Fuels Extension (FFE), simulates fuel dynamics and potential fire behavior and fire hazard over time (Reinhardt and Crookston 2003). Fire and forest managers use the FFE to estimate fire hazard, and fire behavior, under a variety of silvicultural and to evaluate fuel treatment options (Reinhardt and Crookston 2003). This model is used to assist managers prepare environmental assessments for NEPA documentation and for forest planning (forest plan revisions). FFE-FVS simulates changes in fuel loadings from stand dynamics (growth and mortality), management activities (silvicultural treatments), and fuel decomposition (Rebain 2010). FFE-FVS uses existing models and algorithms to simulate fire behavior parameters. Fire intensity is predicated using Rothermel's (1972) spread model as implemented by Albini (1976). Crown fire transition and propagation are predicted using the Van Wagner (1977) and Scott and Reinhardt (2001) models. Tree mortality, fuel consumption, and smoke production predictions are generally based on the algorithms from the First Order Fire Effects Model (FOFEM; Reinhardt et al 1997). However, FFE does not estimate and quantify shrub and herbaceous vegetation loadings, a major contributor to fire behavior. This represents a major limitation of FFE, and affects the accuracy and usefulness of the resulting fire behavior predictions. A full description of FFE-FVS (Reinhardt and Crookston 2003) including chapters on applications, use, and model content, is available in hard copy and online at http://www.fs.fed.us/rm/pubs/rmrs_gtr116.html.

The Fuel Characteristic Classification System (FCCS) provides fire and fuel managers with a consistent and efficient tool to characterize and quantify the full structural complexity and variability of wildland fuels found across diverse forest and nonforest ecosystems (Ottmar et al. 2007, Riccardi et al. 2007a,b,; Sandberg 2007a; Sandberg et al. 2007b; Schaaf et al. 2007. FCCS fire behavior predictions are not estimated from stylized-fuel models (Sandberg et al. 2001), but rater employ the concept of the fuelbed-a complete accounting of all aboveground surface and canopy fuels. FCCS fuelbeds are classified into six horizontal fuelbed strata that represent unique combustion environments: canopy, shrubs, nonwoody fuels (i.e., herbaceous vegetation), woody fuels, litter–lichen–moss, and ground fuels (Fig. 1). Strata are further divided into 18 fuelbed categories and 20 fuelbed subcategories. Fire behavior predictions are based on a reformulated Rothermel rate-of-spread equation (Sandberg et al. 2007b). FCCS predicts surface fire behavior and crown fire potentials based on input fuel characteristics (Table 1) and environmental variables including mid-flame wind speed, slope gradient, and fuel moisture (Ottmar et al. 2007). Surface fire behavior outputs include reaction intensity (Btu ft^{-2} min^{-1} or kJ m^{2}), rate of spread (ft min^{-1} or m min^{-1}), and flame length (ft or m). The FCCS also estimates indexed values, scaled between 0 and 9 and based on baseline environmental conditions that characterize the relative fire potential of the fuelbed. The fire potentials provide a flexible means of expressing any fuelbed as a function of its innate ability to produce fire behavior or effects (Riccardi et al. 2007).

FCCS users cannot create fuelbeds from raw stand examination data or import tree list data from extensive national forest inventory programs (FIA or the FSVeg). FCCS does not directly translate treelist data into FCCS input format, and the model does not simulate vegetation and fuel succession and treatment effects (thinning, pile-and-burn, prescribed fire). Fire and forest managers need a tool to exploit the capabilities of both FVS and FCCS, giving managers the ability to evaluate and simulate silvicultural treatments (e.g., thin from below, prescribed fire, lop/scatter), model forest and fuel succession, and estimate the resulting potential fire behavior based on realistic fuelbeds. FVS2FCCS has the potential to model fire hazard, fire effects, and vegetation succession more realistically and with higher fidelity. Thus, integrating the functions of FVS and FCCS is a logical step in the development of more robust fuel and fire behavior prediction capability for the widely used FVS model. This integration will improve custom fuelbed quantification and provide managers with an alternative, consistent and quantitative approach to estimate fire behavior indices and fire effects from real stand inventory data.

Study Description and Location

Projective Objective

The objective of this project was to build an FVS postprocessor to convert FVS simulated stand data into FCCS fuelbed format (.xml files). Post processors are stand-alone applications that produce specialized output using, as input, files that have been produced by the Forest Vegetation Simulator (FVS). This resulting tool allows users to combine information from FVS about trees and woody fuels with information about shrubs and herbaceous stand components to create FCCS input files (.xml files) that can be used to generate FCCS fire behavior predictions.

Materials and Methods

Development of FVS2FCCS post-processor occurred in three overlapping phases. Phase 1 included development of algorithms to extract and convert FVS simulation data into FCCS input format. Phase 2 included the development of a shrub and herbaceous fuel database for building custom FCCS fuelbeds for each stand in a FVS portfolio, and Phase 3 included the development of a graphical user interface (GUI) to build custom algorithms from FCCS fuelbeds using Phase 1 and the understory vegetation database from Phase 2.

Phase 1—*Develop a suite of algorithms to convert FVS simulated data into FCCS format. This information is sent to a Microsoft Access database.*

We developed a suite of translation algorithms to convert FVS simulated output data into FCCS input format. We developed a keyword component file (.kcp) to calculate FCCS input variables. The .kcp file contains translation algorithms to calculate and convert initial and simulated FVS data into FCCS input format. For each stand and simulation year, the .kcp file generates tables containing FVS simulation results, a tree list file, a snag list file, and a dead fuel loadings file that are stored in a Microsoft® database.

Phase 2—*Develop FVS2FCCS shrub and herbaceous database.*

We manually converted plant association data from more than 100 potential vegetation references into a relational database that provides initial default shrub and herbaceous species presence and coverage for each stand in an FVS portfolio. The complete list of plant association references is found in Appendix F (Potential Vegetation References) of the FSVEG documentation (http://www.fs.fed.us/nrm/fsveg/index.shtml). Each reference lists plant association and associated shrub and herbaceous vegetation. For example, in the Field Guide to Forest Plant Associations of the Wenatchee National Forest (Lillybridge et al. 1995), the plant association code CPG231 represents the *Pinus ponderosa/Calamagrostis rubescens-Agropyron spicatum* (PIPO/CARU-AGSP) plant association. Two shrubs were recorded in the inventory: bitterbrush (*Purshia tridentata*) and serviceberry (*Amelanchier alnifolia*). Coverage for *P. tridentata* and *A. alnifolia* was 3% and 1%, respectively. Eight herbaceous species were recorded (coverage in parentheses): yarrow (*Achillea millefolium*) (3), bluebunch wheatgrass (*Agropyron spicatum*) (22), pinegrass *(Calamagrostis rubescens)* (21), lupines (*Lupinus* spp.) (5), elk sedge (*Carex geyeri*) (11), arrowleaf balsamroot (*Balsamorhiza sagittata)* (4), Idaho fescue (*Festuca idahoenis*) (14), beardless wheatgrass (*Agropyron inerme)* (15). For each stand with the

CPG231 plant association, the post-processor builds FCCS custom FCCS fuelbeds with the aforementioned shrub and herbaceous species composition. Users are then allowed to tailor the initial assignment of default shrub and herbaceous coverage for their particular resource or planning area.
[1]We did not include potential vegetation references from Forest Service Regions 9 (REF_Code 901-907) and omitted species with less than 5% coverage.

Phase 3—*Develop a graphical user interface to build FCCS fuelbeds resulting from Phase 1 algorithms and Phase 2 shrub and herbaceous vegetation database. The GUI will give managers the ability to modify the species composition and coverage for each stand or group of stands before FCCS fire behavior predictions are made.*

We developed a graphical user interface (GUI) to develop multiple FCCS fuelbeds from FVS simulation data. The interface is used to select the FVS output database of interest and build FCCS fuelbeds. Because some information required by FCCS is not available in FVS and other information is based on default values, users must review and edit each temporary fuelbeds before fire behavior modeling in FCCS. Users are asked review the default assignments for shrubs and herbaceous species composition and abundance, as well as other information about mosses and lichens, rotten stumps, fuel moisture and other such variables. All modification and additions are saved and the FVS2FCCS postprocessor created final custom FCCS fuelbeds for every stand and year in the FVS simulation. These FCCS fuelbeds are then batch processes by the FCCS system to generate the associated FCCS estimated of fie behavior.

Code Maintenance, Testing, and Validation

Extensive testing of the FVS2FCCS code has been conducted by the FERA programming staff. This has led to significant error corrections, model changes, and refinements. Additional testing and validation is still required and will be performed over the coming months by early adopters and FVS trainees. We will use feedback received from testers to improve the model and fix programming errors.

Summary Comparison of the Proposed Deliverables and Those Actually Completed

Proposed for Delivery	**Status/Delivered**
JFSP Annual progress reports	Progress reports were completed for each year through 2014
Publish a technical report for managers and an article in *Fire Management Today*.	In progress, Title: *Improving fire behavior prediction using FCCS and FVS*
Integrate the post-processor in FVS and make it available to the Interagency Fuel Treatment Decision Support System.	In progress, working with FVS group and will make code available after testing
Demo of FVS2FCCS at FVS and FCCS training sessions	Planned for 2015 FVS training sessions in November 2015. Plan to attend and present future FVS instructor lead classes in FY16-Fort Collins, CO (January 2016)

Post all data, metadata, publications, and other summaries on the Fire and Environmental Research Applications team website (http://www.fs.fed.us/pnw/fera).	In progress after testing
Final JFSP project report	Final report: Developing a post-processor to link the Forest Vegetation Simulator (FVS) and the Fuel Characteristic Classification System (FCCS)
Presentation to FVS steering committee	Done, April 2014 and April 2015
Presentation to Region 6 Blue Mountains Restoration IDT	Presented overview of conceptual design to team interested in being beta-testers (March 2015)
Present results at professional scientific meetings and various managers' meetings.	Poster and oral presentation Society of American Foresters National Conference, November 3-7, 2015
Refereed publications—1 was promised in the original proposal—One was rejected and 2 are in preparation	Submitted to *Forest Science in 2014 Linking the Forest Vegetation Simulator and the Fuel Characteristic Classification System to improve fuel quantification and fire behavior predictions*, Rejected. Under revision for resubmission in 2016.
Write and publish model documentation.	In development estimated completion July 2016
+Shrub and herbaceous plant association database	Completed a Microsoft Access database including data from several plant association references.
+FVS2FCC User guide and tutorial	In development; estimated completion July 2016
FCCS2FVS GUI	FCCS2FVS GUI version 1.0 completed. Revision to be released as testing and software fixes are implemented. Anticipated next release data July 2016. All programs will be available for download from (http://www.fs.fed.us/fmsc/fvs/software/index.shtml).

+Deliverables in excess of proposed

Key Findings

Although additional testing and analysis is necessary, compared to the traditional fire behavior modeling using stylized fuel models and the Rothermel (1972) spread model (FFE-FVS), FCCS fire behavior predictions (rate-of-spread, reaction intensity, and flame lengths) appear to be significant higher in fuelbeds with a shrub and herbaceous fuel component.

Management implications

This tool will help fire and forest managers predict potential fire behavior and effects by building project-specific custom fuelbeds that include characterization of all fuelbed components that affect fire behavior (flame length, rate-of-spread, and reaction intensity). The FVS2FCCS post-processor can be used to simulate fuel treatment effects and evaluate potential fire behavior by using actual fuel characteristics, instead of stylized-fuel models. Managers can use FVS simulated fuel loadings directly to estimate potential fire behavior. This approach can be evaluated against the FFE-FVS modeling paradigm that use interpolation between stylized-fuel models. Air quality specialists may use FVS2FCCS to calculate fuel loading to be used as inputs to emission an smoke production software package such as Consume (Prichard et al. no date)) and the BlueSky Smoke Modeling Framework (Larkin et al. 2009). This tool provides more opportunities for the use of site-specific and custom fuels data from field-based inventory data, which will help manafers develop thinning treatment prescriptions for reducing wildfire hazard, improve local and regional fire hazard and fuel treatment efficacy assessments and provide support for interdisciplinary teams in illustrating the consequences of proposed treatment alternatives for NEPA documentation.

<u>Future work needed</u>

We need to perform more testing of the system to identify bugs and problems which were not identified during initial testing. Further testing is needed to evaluate other potential bugs with system. These bugs will most likely be identified once the system is tested at the FVS upcoming training sessions. We need to improve the computational time of this tool and develop another GUI to allow managers to assign and modify loadings. FVS can simulate stand succession over many years. Our tool does not project shrub and herbaceous vegetation growth. For each cycle, our model assigns default loading from the structural class of each stand. The relationship between stand density and the presence and absence of shrub and herbaceous material is not tracked in this model. We would also like to link FCCS fire behavior with FVS to estimate fire types (surface, passive, active crown fire) and fire hazard (crowning index, torching index).

This tool does not simulate shrub and herbaceous succession, the user must assign species distribution for each FVS cycle year. Users need to specific specie loadings for each FVS timestep. Research is needed to develop a shrub and herbaceous regeneration model to predict the probability of occurrence, height, and cover of individual shrub, forb, and grass, and fern species. Managers need a model to predict the height and cover of shrubs and herbaceous vegetation (forbs, and grasses) in the understory following disturbances (wildfire, thinning treatments) and succession.

<u>Relationship to other recent finding and ongoing work</u>

Some projects are doing research that may be incorporated with FCCS2FVS. This project should be integrated with the outcomes of the Rangeland Vegetation Simulator (RVS, JFSP# 12-1-02-15) and Interagency Fuels Treatment Decision Support System (IFT-DSS). The RVS estimates succession, growth and yield of non-forest vegetation components which are linked to surface fire behavior fuel models, Fuel Loading Models and Fuel Characteristic Classification System (FCCS) fuelbeds enabling fire behavior and effects simulation at any time in the successional trajectory of a stand. The RVS has added benefits of being sensitive to disturbances including fire, grazing and invasive species such as cheatgrass. Finally, the RVS provides a link to other multi-million dollar interagency projects such as Ecological Sites making it cost effective, transparent and uniquely positioned to make a positive difference in the performance of the FVS.

<u>Acknowledgements</u>

We thank the Joint Science Program, PNW Research Station, and Southern Nevada Public Land Management Act (SNPLMA) for funding this project and all the University of Washington students who worked on the database.

Literature Cited

Albini, F.A. 1976. Estimating wildfire behavior and effects. Gen. Tech. Rep. INT-30. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 92 p.

Andrews, P.L. 1986. BEHAVE: fire behavior prediction and fuel modeling system--BURN subsystem, Part 1. Gen. Tech. Rep. INT-194. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 130 p.

Anderson, H.E. 1982. Aids to determining fuel models for estimating fire behavior. Gen. Tech. Rep. INT-122. Ogden, UT. U.S. Department of Agriculture, Forest Service, 22 p

Crookston, N.L.; Roelke, R.C.; Burnell, D.G.; Stage, A.R. 1978. Evaluation of management alternatives for lodgepole pine stands using a stand projection model. In: Kibbee, D. L.; Berryman, A. A.; Amman, G. D.; Stark, R. W., Eds. Theory and practice of mountain pine beetle management in lodgepole pine forests. Proceedings of a Symposium, 25-27 April 1978. Washington State University, Pullman, WA. pp. 114-122. Forest, Wildlife and Range Experiment Station, University of Idaho, Moscow, ID.

Dixon, G.E. comp. 2002. Essential FVS: A user's guide to the Forest Vegetation Simulator. Internal Rep. Fort Collins, CO: U. S. Department of Agriculture, Forest Service, Forest Management Service Center. 244 p. (Revised: August 12, 2011)

Finney, M.A., Cohen, J.D. 2003. Expectation and evaluation of fuel management objectives. In Proceedings of the Conference on the Fire, Fuel Treatments, and Ecological Restoration, 14–17 April 2003. Proc. RMRS-P-29. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station pp. 353-366.

Finney, M.A. 1998. FARSITE: Fire Area Simulator-model development and evaluation. Res. Pap. RMRS-RP-4, Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 47 p.

Frankel, S. J., technical coordinator. 1998. User's guide to the western root disease model, version 3.0. Gen. Tech. Rep. PSW-165. Albany, CA: U. S. Department of Agriculture, Forest Service, Pacific Southwest Research Station. 164p.

Graham, R.T., Harvey, A.E., Jain, T.B., Tonn, J.R. 1999. The effects of thinning and similar stands treatments on fire behavior in western forests. Gen. Tech. Rep. PNW-GTR-463. Portland, OR: U.. Department of Agriculture, Forest Service Pacific Northwest Research Station.

Johnson, M.C., Kennedy, M.C., Peterson, D.L. 2011. Simulating fuel treatment effects in dry forests of the western United States: testing the principles of a fire-safe forest. Canadian Journal of Forest Research 41: 1018-1030.

Larkin, N.K., O'Neill, S.M., Solomon, R., Raffuse, S., Strand, T., Sullivan, D.C., Krull, C., Rorig, M., Peterson, J.L., Ferguson, S.A. 2009. The BlueSky smoke modeling framework. International Journal of Wildland Fire 18: 906-920.

Lillybridge, T.R., Kovalchik, B.L., Williams, C.K., Smith, B.G., 1995. Field Guide for Forested Plant Associations of the Wenatchee National Forest. USDA Forest Service. Gen. Tech. Rep. GTR-PNW-359. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Noonan-Wright, E.K., Vaillant, N.M., Reiner, A.L. 2014. The effectiveness and limitations of fuel modeling using the fire and fuels extension to the forest vegetation simulator. Forest Science 60 (2): 231-240.

Ottmar, R.D., Sandberg, D.V., Riccardi, C.L., Prichard, S.J. 2007. An overview of the fuel characteristic classification system – quantifying, classifying, and creating fuelbeds for resource planning. Canadian Journal of Forest Research 37: 2383-2393.

Marsden, M. A., Eav, B. B., Thompson, M. K. 1994. User's guide to the Douglas-fir beetle impact model. Internal Rep. MAG-93-9. Fort Collins, CO: U. S. Department of Agriculture, Forest Service, Forest Pest Management Methods Application Group. 160p.

Peterson, D.L., Johnson M.C., Agee, J.K., Jain, T.B., McKenzie, D., Reinhardt, E.D. 2005. Forest structure and fire hazard in dry forests of the Western United States. Gen. Tech. Rep. GTR-PNW-628. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Prichard, S.J., Ottmar, R.D., Anderson, G.K. no date. CONSUME 3.0 user's guide. Seattle, WA: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Pacific Wildland Fire Sciences Laboratory. 233 p.

Reinhardt, E., Crookston, N.L. 2003. The Fire and Fuels Extension to the Forest Vegetation Simulator. Gen. Tech. Rep. RMRS-GTR-116. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 209 p.

Reinhardt, E.D., R.E. Keane and J.K. Brown. 1997. First Order Fire Effects Model: FOFEM 4.0, user's guide. Gen. Tech. Rep. INT-GTR-344. , Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station 65 pp.

Rebain, S. A. comp. 2010 (revised March 23,2015). The Fire and Fuels Extension to the Forest Vegetation Simulator: Updated Model Documentation. Internal Rep. Fort Collins, CO: U. S. Department of Agriculture, Forest Service, Forest Management Service Center. 403p

Riccardi, C.L., Ottmar, R.D., Sandberg, D.V., Andreu, A., Elman, E., Kopper, K., Long, J. 2007a. The fuelbed: a key element of the Fuel Characteristic Classification System. Canadian Journal Forest Research 37(12): 2394-2412.

Riccardi, C.L., Prichard, S.J., Sandberg, D.V., Ottmar, R.D. 2007b. Quantifying physical characteristics of wildland fuels using the Fuel Characteristic Classification System. Canadian Journal of Forest Research 37: 2413-2420.

Rothermel, R.C. 1972. A mathematical model for predicting fire spread in wildlands fuels. Res. Pap. INT-115. Ogden,UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 40 p.

Sandberg, D.V., Ottmar, R.D., Cushon, G.H. 2001. Characterizing fuels in the 21st Century. International Journal of Wildland Fire 10: 381-387.

Schaaf, M. D., Sandberg, D.V., Schreuder, M.D., Riccardi, C. L. 2007. A Conceptual Framework for Ranking Crown Fire Potential in Wildland Fuelbeds. Canadian Journal of Forest Research. 37(12): 2464-2478.

Scott, J.H. 1999. NEXUS: A system for assessing crown fire hazard. Fire Management Notes 59 (2): 20-24.

Scott, J.H., Burgan, R. E. and. 2005. Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model. RMRS-GTR-153. USDA Forest Service. Fort Collins, Colorado, USA.

Van Wagner, C.E. 1977. Conditions for the start and spread of crown fire. Canadian Journal of Forest Research 7: 23-34.