Environmental Modelling & Software 80 (2016) 225–244

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft

Modeling fuels and fire effects in 3D: Model description and applications

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ARTICLE INFO

Article history:
Received 24 July 2015
Received in revised form
1 March 2016
Accepted 4 March 2016
Available online 22 March 2016

Keywords:
FuelManager
CAPSIS
Fuel treatment
Fire effects
FIRETEC
WFDS

ABSTRACT

Scientists and managers critically need ways to assess how fuel treatments alter fire behavior, yet few tools currently exist for this purpose. We present a spatially-explicit-fuel-modeling system, FuelManager, which models fuels, vegetation growth, fire behavior (using a physics-based model, FIRETEC), and fire effects. FuelManager's flexible approach facilitates modeling fuels across a wide range of detail. Large trees or shrubs with specific coordinates are modeled as individual "*Plants*", while understory plants are modeled as collections of plants called "*LayerSets*". Both *Plants* and *LayerSets* contain various fuel particles (leaves, needles, twigs) with various properties including shape, size and surface area to volume ratio. A wide range of vegetation and treatments can be modeled, analyzed quantitatively and visualized in a 3D viewer. We describe the modeling approach and demonstrate fuel modeling at different levels of detail, fuel treatment and fire effects capabilities. Detailed model equations are provided in the Appendices.

Software availability

Name of software: FuelManager
Developers: INRA
Contact address: URFM, INRA, Domaine Saint Paul, Site Agroparc, CS 40,509–84914 Avignon Cedex 9, France. Email: francois.pimont@avignon.inra.fr
Availability: The software is available on request.
Documentation: online (http://capsis.cirad.fr/capsis/help/fireparadox) and report (Lecomte et al., 2010).
Year first available: 2010
Hardware required: MS Windows, Linux or Mac OS.
Programming language: Java 1.7. Contact the corresponding author (francois.pimont@avignon.inra.fr) for further details.
Program size: 125 MB.

Symbols, abbreviations and definitions
BD: Fuel bulk density (kg m^{-3})
BH: Base height (m), for *Layers*
CBH: Crown base height (m), for *Plants*
C: Cover fraction, for *Plant Stands*, *Layers and LayerSets*
C_{ini}: Cover fraction in *Plant Stands*, before fuel treatment
CD: Crown diameter (m), for *Plants*
Cover fraction: Fraction of the ground area (defined by a *Polygon*) covered by fuel
Crown Geometry: Set of crown diameters (relative to maximum crown diameter) for several relative heights in crown
D: Crown-space (m) for crown-space thinning
DBD: Live fuel bulk density (kg m^{-3})
DBH: Diameter at breast height (cm), for *Plants*
D_{dom}: Dominant diameter of a *Plant Stand* (cm)
DMC: Dead fuel moisture content (%), for *Plants* and *Layers*
CAPSIS: Computer-Aided Projection of Strategies In Silviculture
FCCS: Fuel Characteristic Classification System
FFE-FVS: Fire and Fuels Extension to the Forest Vegetation Simulator

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http://dx.doi.org/10.1016/j.envsoft.2016.03.003
1364-8152/

FireParameters: Information regarding physical conditions in the neighborhood of a *Plant*
FM: FuelManager
FuelMatrix: Detailed voxelized representation of fuel items (*Plant* and *LayerSets*)
BA: Basal area of a *Plant Stand* (stem ha^{-1})
BA_{ini}: Basal area of a *Plant Stand*, before fuel treatment (stem ha^{-1})
H: Height (m), for *Plants* and *Layers*
H_{dom}: Dominant height of a *Plant Stand* (m)
ICFME: International Crown Fire Modeling Experiment
L: Clump size (m), for *Layers*
LAI: Leaf area index of a *Plant Stand* and *LayerSets*
LayerSet: Group of plants not represented individually as fuel item; Collection of *Layers*
Layer: Fuel component of a *LayerSet*, as clumps of a group of *Particles* that are identically spatially distributed.
LBD: Live fuel bulk density (kg m^{-3}).
LMC: Live fuel moisture content (%), for *Plants* and *Layers*
Load: Fuel mass per unit of square ground (kg m^{-2})
MC: Moisture content (%), for *Plants* and *Layers*
MVR: Mass-to-volume ratio (kg m^{-3}), for *Plants* and *Layers*
N: Stem density of a *Plant Stand* (ha^{-1})
Particle: Fuel element with well-defined physical properties (MVR, SVR, MC)
Plant: Individually identified fuel item
Polygon: used as a *Stand* base (*Plants*) or *LayerSet* base
Scene: Chosen piece of landscape for fuel modeling; contains *Plants* (in one or several *Stands*) and *LayerSets*
Severity: Set of synthetic parameters describing fire damage to a *Plant*
SpatialGroup: *Layer* group number, for space competition
SG: Spatial group
speciesFile: Input file containing equations and parameters to model a *Plant* species
Stand: Collection of *Plants* with position inside a given *Polygon* (that can match the whole *Scene*)
Step: The state of the *Scene* at particular time under a particular scenario
SVR: Surface-area-to-volume ratio (m^{-1}), for *Plants* and *Layers*
WFDS: Wildland–Urban Interface Fire Dynamics Simulator

1. Introduction

Numerous factors have led to increases in fire frequency, area burned or fire severity in many parts of the world over the last few decades (Moreira et al., 2011; Miller et al., 2009; Turetsky et al., 2011). Combined with trends of an expanding wildland–urban interface, these changes have increased fire hazard. Fuel treatments, such as thinning forests or clearing of shrubs, are often proposed as a method for reducing fire hazard. To properly assess hazard and potentially mitigate it, analysts and managers must be able to quantify fuel conditions and potential fire behavior, both for the present and in the future. In the United States, systems that integrate both vegetation and fire modeling have been developed and are widely used in assessments of fuel treatments, at the scale of individual stands (FFE-FVS, Crookston and Dixon, 2005; Reinhardt and Crookston, 2003; FCCS, Ottmar et al., 2007) and for landscapes (Ager et al., 2012), typically for near-(years) to medium-term (decadal) temporal periods. A different class of models, called landscape-fire-succession models (LFSMs, Keane et al., 2004), such as FIRESCAPE (Cary and Banks, 2000), SIERRA (Mouillot et al., 2001) or LANDIS (Mladenoff, 2004), examine how interactions between vegetation, disturbance and management actions influence fire regimes, typically over longer temporal periods (centuries to millennia). Both shorter-term and longer-term-modeling systems typically must combine several different components and processes, including the assimilation of field data for fuel initialization, forest demographics (recruitment and natural mortality over time), individual tree growth and biomass accumulation, and response to disturbances or management actions. Several other fuel modeling systems have been developed, typically reflecting particular ecosystems as well as related management approaches (see Krivtsov et al., 2009 for a review). These systems span a range of scales and level of detail.

At present, the fire modeling systems commonly used in the United States are built upon the same fire behavior modeling framework, which links a quasi-empirical surface fire spread and flame length model (Rothermel, 1972) with crown fire initiation (Van Wagner, 1977) and crown fire spread models (Rothermel, 1991). This fire-modeling framework facilitates very fast calculations but is limited with regard to both fuel characterization and the underlying processes of fire spread. Assumptions of fuel homogeneity and steady-state fire spread are central to this modeling framework. These assumptions reduce the system's applicability in forest environments where fuels are highly heterogeneous and fire behavior is often dynamic and transitional. Perhaps most critically, changes in fuels often result in additional changes in the fire environment, such as wind flow, with important feedbacks to fire behavior. The simplifying assumptions in these commonly-used fire behavior models are problematic for modeling fires in forest canopies (Cruz and Alexander, 2013) and especially forest canopies impacted by certain disturbances such as beetle attacks (Jolly et al., 2012; Moran and Cochrane, 2012). Moisture content or other fuel properties in such disturbance-altered fuel types are typically out of the range of the data used for the calibration of semi-empirical models. In addition, the resulting fuel distributions can be quite heterogeneous, which cannot be accounted for in those models. The feedbacks on fire behavior can be complex and transient (Hoffman et al., 2015a). More importantly, many aspects of how fuel treatments alter fire behavior and fire effects are still unknown, leaving fuel and fire managers without clear guidance as to the most effective alternatives or appropriate strategies for managing many ecosystems.

Recently, advanced physic-based fire behavior models, such as WFDS (Mell et al., 2007) and FIRETEC (Linn and Cunningham, 2005; Pimont et al., 2009; Dupuy et al., 2011) have been used to model fire behavior in highly heterogeneous fuel (Linn et al., 2005; Pimont et al., 2011a; Parsons et al., 2011). These models represent both fuels and key fire behavior processes with much greater detail than the commonly used semi-empirical models, and facilitate exploration of aspects of fuel/fire interactions that is not possible if assumptions of homogeneity are used. Such explorations include the influences of heterogeneous fuels on the local wind flow and the resulting impacts on fire behavior (Pimont et al., 2011a). They can also be used to model fire behavior in disturbance-altered fuel types, such as those following bark beetle outbreaks or budworm defoliations (Hoffman et al., 2012; Linn et al., 2013; Cohn et al., 2014; Hoffman et al., 2015a). Although physically-based models show promise for detailed examination of fuel/fire/atmosphere interactions, they have several limitations, including expertise, code availability, computational costs, limited number of validations against experimental data, etc. Another limitation is fuel inputs that use specific formats and require much more details than quasi-empirical models, such as locations and dimensions of individual trees, and spatial distributions of understory fuels or tridimensional distributions of fuel mass, surface area and moisture content. Such detailed data are laborious to collect and generate, and are often only available for small areas. There is thus a significant need for a modeling platform to facilitate the development of heterogeneous fuel beds for large areas based on available data and