

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

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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.

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Software availability

Name of software: FuelManager

Developers: INRA

Contact address: URFM, INRA, Domaine Saint Paul, Site Agroparc,

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francois.pimont@avignon.inra.fr

Availability: The software is available on request.

Documentation: online ([http://capsis.cirad.fr/capsis/help/](http://capsis.cirad.fr/capsis/help/fireparadox)

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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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 fire 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

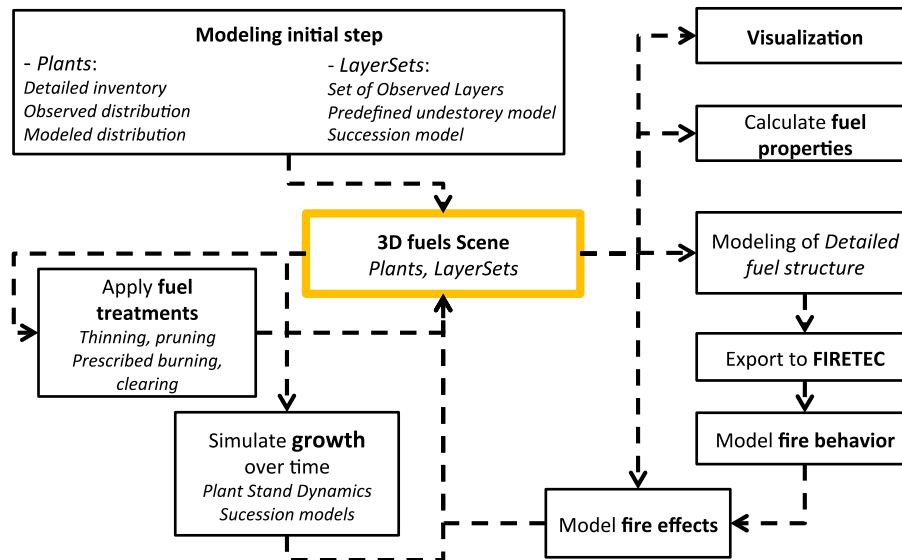


Fig. 1. Overview flow diagram for the FuelManager model and its interaction with FIRETEC.

to evolve and manipulate these fuel beds to mimic ecological processes and anthropogenic or natural disturbances. Such a platform would eliminate significant fractions of the effort required to study the effects of fuel-bed properties and fire by linking fuel, fire-behavior and fire-effects models. It would also improve the replicability and transparency of fire modeling studies, by providing a means by which fuel representations used in physics-based fire simulations can be exchanged and used by other researchers. At present there is no easy means by which detailed fuels data can be reproduced by another researcher. These needs call for the development of new tools to virtually manage fuel used in physically-based models.

In this paper we introduce FuelManager, a model designed to address these needs (Rigolot et al., 2010). We describe the model and demonstrate its application with several examples.

2. Model description

2.1. Model overview

FuelManager is a modeling system, hereafter referred to as *FM*, designed to facilitate the quantification, characterization and visualization of fuels, and enable the study of fire behavior response to fuel changes, either over time through natural growth or as a result of disturbances such as fire or management actions such as thinning. The overall intent of the model is to provide a flexible framework enabling detailed fuel/fire interactions studies through simulation modeling. The primary function of *FM* is to generate a quantitative, spatially-explicit representation of wildland fuels, which can then be used for a variety of purposes, including providing input data for physics-based models.

An overview of *FM* is presented in Fig. 1. An initial *Scene* is first modeled as a collection of realistic spatially-explicit fuel items (*Plants* and *LayerSets*, described in section 2.2). The methods for developing the initial fuel item distributions are described in section 2.3 and require several input parameters. Further manipulation of the fuels in a *Scene* resulting from natural growth, disturbances or management actions, are described in section 2.4; these changes over time result in a succession of *Steps* (Dufour-Kowalski et al., 2012), which contain the state of the *Scene* for each point in time over the progression. Initial and further *Steps* can

be visualized and fuel properties examined in the 3D Editor (section 2.5). Fuel distributions at any *Step* can be exported to a format compatible with physics-based models, such as FIRETEC (section 2.6). Fire effects, calculated using a combination of empirical and physical models, including fire behavior models such as FIRETEC, are described in section 2.7. Note that all stochastic processes involved in the system are by default initialized with a random seed, which is a key point for simulation replicability.

FM was implemented as a module of the CAPSIS (Computer-Aided Projection of Strategies in Silviculture) platform.¹ CAPSIS is a collaborative open-source software within which a wide range of forestry-related models have been developed using a common architecture that provides I/O functions, analysis, visualization tools, shared libraries and source code (Dufour-Kowalski et al., 2012). The conceptual framework of *FM* and the main modeling components are described here, but more details can be found in the user guide.²

2.2. Plants and LayerSets

Fuels can be modeled in two different ways in *FM*. Which approach is better depends on the level of detail that is practical, based on data availability, and whether distinguishing individual plants from one another is important. Larger plants, such as trees or tall shrubs, can be identified as individual, discrete entities (*Plant*) in the model, whereas a layerset (*LayerSet*) is used to describe a group of plants or of fuel elements such as shrubs or litter that are too small, too numerous and/or not well characterized enough to represent individually (Fig. 2). The user can decide to use either *Plant* or *LayerSet*, or more often both, depending on data available, expected relevant scales and fire model sensitivity. Key fuel characteristics are associated with both *Plants* and *LayerSets* representation as attributes. Some of the attributes are common to both *Plants* and *Layersets*. They both include descriptions of multiple *Particle* types (leaves, needles and twigs of various sizes, either live or dead, as well as Coarse Woody Debris). The *Particles* are characterized by their mass-to-volume ratio (MVR, in kg m^{-3}), surface-

¹ <http://www.inra.fr/capsis>.

² http://capsis.cirad.fr/capsis/help_en/fireparadox.

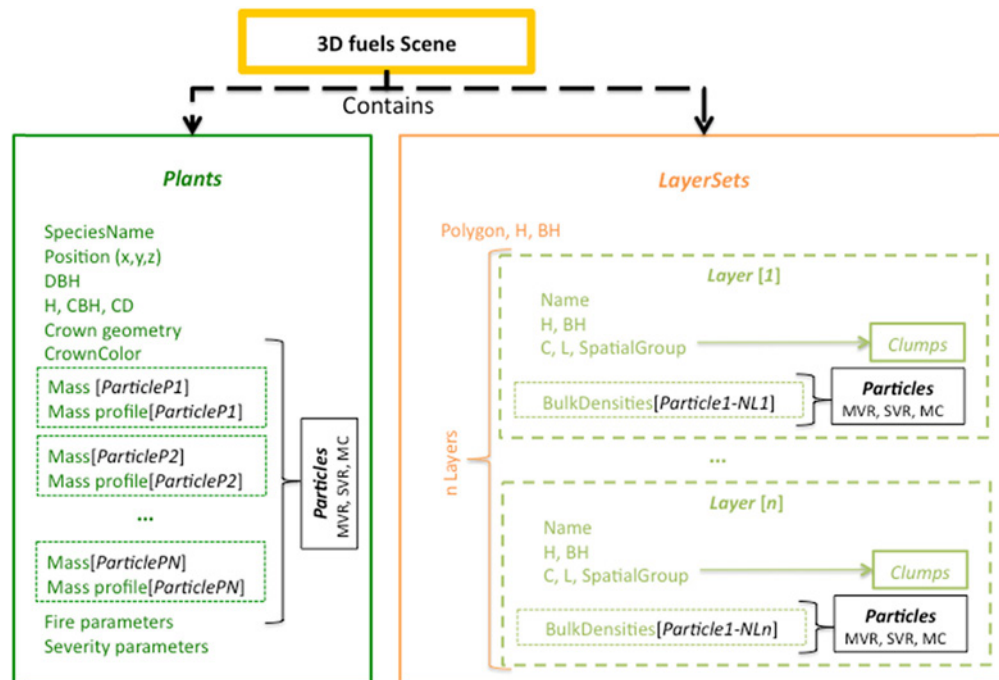


Fig. 2. Main attributes of the fuel items in Scene (Plant, LayerSet).

area-to-volume ratio (SVR, in m^{-1}) and moisture content (MC, in %, which is expressed as the mass of water in a particle type sample divided by its dry fuel mass). Most physics-based fire modeling to date has focused on the combustion of thin particles only. Some capabilities exist to model combustion in Coarse Woody Debris, but these capabilities are yet rather limited in scale. For this reason, although *FM* can be used to model such fuels, we do not discuss them much in the applications section.

A *Plant* has a position (x, y, z) in the *Scene* (in meters), a diameter at breast height (DBH, in cm), crown and stem dimensions in meters: height (H), crown base height (CBH), crown diameter (CD), and a *Crown Geometry*. A collection of *Plants* with positions inside a given closed polygon (with uncrossed sides and irregular in shape) is called a *Stand*. *Crown Geometry* is a geometric profile consisting of a series of crown diameters (relative to maximum crown diameter), for several relative heights, relative to the length of the crown. This list is used to model the shape of each individual *Plant* crown, assuming axial symmetry of each crown around the trunk axis. Each particle type associated with a given *Plant* has a mass (kg) and a vertical distribution with which the particles are located within the crown. The masses are typically computed using DBH and H allometry. The equations and parameters required to model a given species are specified in a parameter file (*speciesFile*). The user can modify this file to change equations used for existing species or to add new ones. Example equations used for the Aleppo pine *Plant* model are provided in Appendix A. The list of equations available for parameterization of each model component are available online.³

A *LayerSet* is a flexible approach for representing groups of plants when it is impractical to describe them as individual plants. Within a *LayerSet*, various vegetation types or fuel components can be mixed together and assigned different characteristics. A *LayerSet* occupies a volume of space within a *Scene* and is represented as a right prism with a base face parallel to the ground. This volume, in

which the mixture of vegetation is located, is characterized by a polygon as the base, and a height (H , in m). As for *Plant Stands*, the polygon must close and cannot have lines that cross, as such aspects are problematic for calculations of area or other properties. The different vegetation types or fuel components that make up a *LayerSet* (shrub species, grass, litter, duff, etc.) are referred to as *Layers*. Each *Layer* is characterized by a cover fraction (C), a clump size (L , in m), a base height (BH , in m), a height (H , in m) and contains one or more particle types specified with a load (kg m^{-2}) and a vertical distribution. Even though a *Layer* spans the horizontal extent of a *LayerSet*, it is possible to account for the fact that the fuel can be aggregated into clumps that are distributed throughout the *LayerSet* volume with spaces between them. The locations of clumps are not specified immediately when a *Layer* is created for computational and memory efficiency (see section 2.6), but they are conceptualized as though they are numerous cylindrical regions that stretch over the vertical extent of the *Layer*. Clumps will be effectively created only when the *FuelMatrix* is built, for memory cost limitation (section 2.6). How the clumps are located when the *FuelMatrix* is built depends on the user specification of whether they compete for space or not. If the clumps in a given *Layer* compete with clumps in a different *Layer*, they will be located such that they do not occupy the same space (i.e., no overlap); non-competing clumps can overlap. The overall load and cover fraction of the *LayerSet* are computed according to the combined properties of the *Layers* that make up the *LayerSet*. The combination of *Layers* and their properties can be either specified by the user, based on predefined fuel types or modeled (see Appendix C for examples).

2.3. Initial fuel beds and assimilating input data

FM allows various ways to develop both *Plants* and *LayerSets*, based on the available level of detail for fuels inputs, ranging from very detailed to coarse in terms of fuels information. The various approaches for representing vegetation based on different levels of

³ http://capsis.cirad.fr/capsis/help_en/firelib/speciesfile.

detail are briefly reviewed here, but more details can be found in the online documentation.⁴

FM provides several methods to populate a specified polygonal area with individual *Plants*. The most straightforward, and most specific approach, is called a *Detailed Plant Inventory*. This method is used when individual tree attributes and positions are known, as is commonly the case in stem-mapped research data sets. If individual *Plant* attributes and positions are not known, FM can populate the *Stand* in a polygon with various spatial arrangements using an *Observed Plant Distribution*, using a DBH and H class inventory (for example, Alexander et al., 2004). If the *Plant Distribution* of DBH and H is not available from field data, the *Plant Stand* can be modeled using a *Modeled Plant Distribution*. The *Modeled Plant Distribution* is based on a statistical approach to developing a list of *Plants* with realistic DBH and H distributions from a few simple characteristics of the stand such as dominant height, stand age and stem density. An example of this approach is provided in Appendix B.

Both the *Observed* and *Modeled Plant distribution* approaches require an algorithm to spatially distribute the *Plants* within a *Stand* (i.e., within a specified polygon). The distribution can be simply random, but this can result in areas in which overlapping tree crowns produce fuel loads that are unnaturally high. A more sophisticated algorithm was derived from the “hard core” statistical method (Cressie, 1993). This method was slightly modified to integrate *Crown Geometries* and to allow a limited degree of crown intersection when the *Plant* cover fraction is high. In this iterative algorithm, the position of each *Plant* position is set one at a time, starting with the largest plants and then placing the smaller plants in order of decreasing size. For a given *Plant*, assuming that the positions of larger *Plants* are already set, a trial position is chosen randomly within the *Stand*. The crown volume intersection between this *Plant* and larger ones is computed. If there is no intersection, the chance of this trial position being accepted is set to 100% and the location of the *Plant* is accepted. If a volume intersection is found, the probability of the trial location being accepted is decreased based on a function that diminishes the probability as intersected volume increases. If the trial location is not selected, then another trial location is chosen and tested, but with each subsequent trial the probability of acceptance is increased. This method was inspired by “simulated annealing”, which is an efficient optimization technique (Kirkpatrick et al., 1983). Even if no explicit competition is modeled here, this algorithm will provide a solution, limiting crown intersection volume to match realistic biological principles, at a low computational cost. Note that the crown volume intersection is computed in 3D using *Plant Crown geometry*, so that understory or suppressed *Plants* are preferentially located underneath dominant *Plants*. An example *Plant* distribution computed with this algorithm can be seen on Fig. 3. In this *Scene*, two rectangular polygons were used to distribute the *Plants* in two *Stands*, separated by a forest road. *Plants* distribution parameters are specific to each *Stand* (within a polygon), so FM may distribute *Plants* in different ways in each stand.

Similarly, polygons can also be used to define different *LayerSets*. A *LayerSet* can be defined as a *Set of Observed Layers* (e.g. of *Layer* parameterization in Table 1), or using a *Predefined Understory Model* (static predefined fuel complexes), or using a *Succession Model*. An example of succession model for Kermes oak garrigue is provided in Appendix C.

2.4. Fuel modifications

2.4.1. Simulating vegetation growth over time: Plant Stand Dynamics and LayerSet Succession models

The model used for simulating growth in *Plants* over time is an individual-tree, distance-independent growth model that predicts individual evolution of *Plant* DBH and H over a year. As an example, the model for Aleppo Pine growth (Dreyfus et al., 2001) is driven by regional site index curves (Cohert and Duplat, 1993) linking stand dominant height growth over time to stand age, depending on an index value that denotes the quality of site conditions. For any site, this index can be determined using its present [age, dominant height] pair. Three other relations composing the growth model are a diameter growth equation, a height-diameter equation and a mortality probability equation (Dreyfus et al., 2001).

Subsequent points in time, referred to as the “Steps” of *LayerSets* are simulated with a *Succession model*, that combines growth in height and biomass accumulation. An example model used for Kermes oak garrigue is provided in Appendix C.

2.4.2. Application of fuel treatments

Fire managers commonly use thinning and pruning to reduce canopy fuels and understory clearing or prescribed burning to decrease shrubland and understory fuels. FM can represent the effects of *Thinning* and *Pruning* of *Plants* and mechanical *Clearing* or prescribed burning of *LayerSets*, resulting in new *Steps* for the *Scene*. When a treatment is applied to a *Plant* or a *LayerSet*, the user can either decide to remove collected fuel from the scene or to keep it in the scene as surface fuel in a *LayerSet* underneath treated *Plants* (retention of activity fuel option). In this latter case, the user will have to specify litter depth and moisture content. Among a variety of *Thinning* possibilities in FM, it is possible to simulate fuel management that targets achieving space between *Plant* crowns in a realistic manner (*Crown spacing*). The algorithm simulates line transects along which plants are selected for thinning. The field practice of walking these transects is commonly referred to as “marking walks” and thus are referred to as such in the model. Some *Plants* are thinned one at a time, keeping preferentially the largest *Plants* and removing the surrounding ones, to make sure that the distance between crowns is always greater than a given value D. The sequence of *Plant* cutting during the *Crown spacing* treatment is decomposed in Fig. 4.

The *Pruning* algorithm defines a new CBH equivalent to the pruning height. The initial CBH is conserved to keep unmodified the crown shape above pruning height, but the corresponding fuel is removed below pruning height.

When the *Clearing* of *LayerSet* is mechanical, the bulk density and height of shrubs or other understory fuels are set to zero. Similar to the *Plant* treatment algorithms above, activity fuels can be either removed from the *Scene* or added to the surface fuels (retention of activity fuel option). When the clearing of *LayerSet* aims at representing prescribed burning, the user can specify that a fraction of the initial fuel remains, depending on the severity of the prescribed burning he wants to simulate. Moisture content of the remaining fuel can also be modified if this fuel is assumed to be killed by the prescribed burning.

2.5. Scene visualization, editing and fuel property calculations

The FM has a versatile and powerful 3D editor (Fig. 3), which combines the CAPSIS 3D viewer's options to change perspective with interactive “orbit”, “translate”, and “zoom” options. Additionally, interactive *Scene* manipulation tools include: select, move, add and remove objects, draw lines and polygon, etc. The editor provides a state panel in which fuel properties are computed for the

⁴ http://capsis.cirad.fr/capsis/help_en/fireparadox/gui/fminitialdialog.

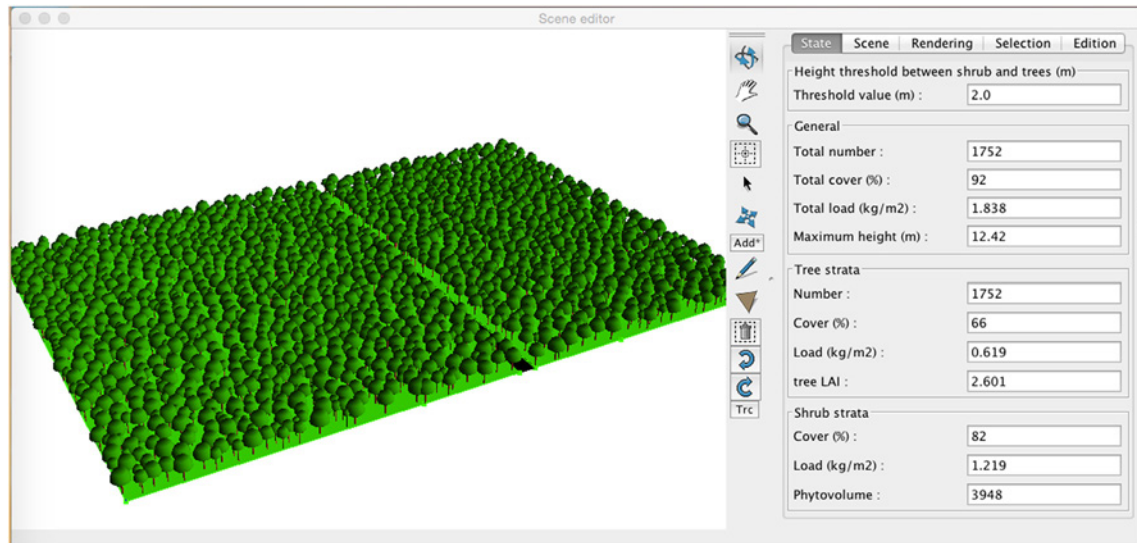


Fig. 3. Aleppo pine distribution using the 3D editor, made of two rectangular 60 year old *Stands*, with $N = 300$ stems per ha and a dominant height at 50 years $H_{dom}^{50} = 12\text{m}$ (medium fertility). *Stands* were separated by a 10 m road. The understory is a kermes oak garrigue, undisturbed during the last 10 years. The control panel is on the right.

Table 1

Example *Layer* sections in the input file for *FM*, used to generate the FireFlux *Scene* shown in Fig. 7. Data were derived from Clements et al. (2007) and personal communications with experiment participants.

#Layer properties												
LayerSet	Species	H	BH	C	L	SG	LMC	DMC	LBD	DBD	MVR	SVR
1	Trees	12.0	2.0	0.80	6.	0	200	0.0	0.05	0.0	500	6000
2	Trees_UT1	0.1	0.0	1.0	2.	1	100	13.	0.00	0.5	500	5000
2	Trees_UT2	0.8	0.0	0.50	2.	2	100	13.	0.05	0.0	500	5000
3	Trees	12.0	2.0	0.80	6.	0	200	0.0	0.05	0.0	500	6000
4	Trees_UT1	0.1	0.0	1.0	2.	1	100	13.	0.00	0.5	500	5000
4	Trees_UT2	0.8	0.0	0.50	2.	2	100	13.	0.05	0.0	500	5000
5	Trees	12.0	2.0	0.80	6.	0	200	0.0	0.05	0.0	500	6000
6	Trees_UT1	0.1	0.0	1.0	2.	1	100	13.	0.00	0.5	500	5000
6	Trees_UT2	0.8	0.0	0.50	2.	2	100	13.	0.05	0.0	500	5000
7	Trees	12.0	2.0	0.80	6.	0	200	0.0	0.05	0.0	500	6000
8	Trees_UT1	0.1	0.0	1.0	2.	1	100	13.	0.00	0.5	500	5000
8	Trees_UT2	0.8	0.0	0.50	2.	2	100	13.	0.05	0.0	500	5000
9	Trees	12.0	2.0	0.80	6.	0	200	0.0	0.05	0.0	500	6000
10	Trees_UT1	0.1	0.0	1.0	2.	1	100	13.	0.00	0.5	500	5000
10	Trees_UT2	0.8	0.0	0.50	2.	2	100	13.	0.05	0.0	500	5000
11	Trees	12.0	2.0	0.80	6.	0	200	0.0	0.05	0.0	500	6000
12	Trees_UT1	0.1	0.0	1.0	2.	1	100	13.	0.00	0.5	500	5000
12	Trees_UT2	0.8	0.0	0.50	2.	2	100	13.	0.05	0.0	500	5000
13	Trees_Spar	12.0	2.0	0.1	10.	0	200	0.0	0.05	0.0	500	6000
14	LowGrass	0.1	0.0	1.0	0	1	200	0.0	0.5	0.0	500	5000
15	Grass	1.5	0.0	0.96	2.	0	200	13.0	0.0	0.69	500	5000
15	Shrub	1.5	0.0	0.04	2.	0	200	13.0	0.69	0.0	500	5000
16	Grass	1.5	0.0	0.96	2.	0	200	13.0	0.0	0.69	500	5000
16	Shrub	1.5	0.0	0.04	2.	0	200	13.0	0.69	0.0	500	5000
17	Grass	1.5	0.0	0.96	2.	0	200	13.0	0.0	0.69	500	5000
17	Shrub	1.5	0.0	0.04	2.	0	200	13.0	0.69	0.0	500	5000
18	LowGrass	0.1	0.0	1.0	0	1	200	0.0	0.5	0.0	500	5000

H: layer (m); BH: base height (m); C: cover fraction; L: clump size (m); SG: spatial group; LMC/DMC: live/dead moisture content (%); LBD/DBD: live/dead bulk density (kg m^{-3}); MVR: mass-to-volume ratio (kg m^{-3}); SVR: surface-area-to-volume ratio (m^{-1}).

whole fuel *Scene* or for a specific polygon (*Stand* or *LayerSet*) when one is selected. Fuel properties computed include number of plants, loads and cover fractions per strata, phytovolume for the lower strata and Leaf Area Index for the upper strata. These properties can be exported for further analysis (an application is shown in section 3.1.2). Once an item (*Plant*, *LayerSet*) is selected, its properties can be seen in the “Selection” tab.

Several rendering options are available in the “Rendering” tab for *Plant* and *LayerSet*, including a sketcher with color selection by

species, height threshold and with or without fire damage visualization (section 3.2). The color choice can be parameterized in the input file and modified in the “Rendering tab”. When no color is specified in the input file for a *LayerSet*, *FM* computes a color between yellow and green according to the amount of moisture and load available, so that dry and light *LayerSets* are rendered more yellowed than wet and heavy ones.

Special attention has been paid to the robustness and efficiency of *Scene* manipulation, because 3D visualization is computationally

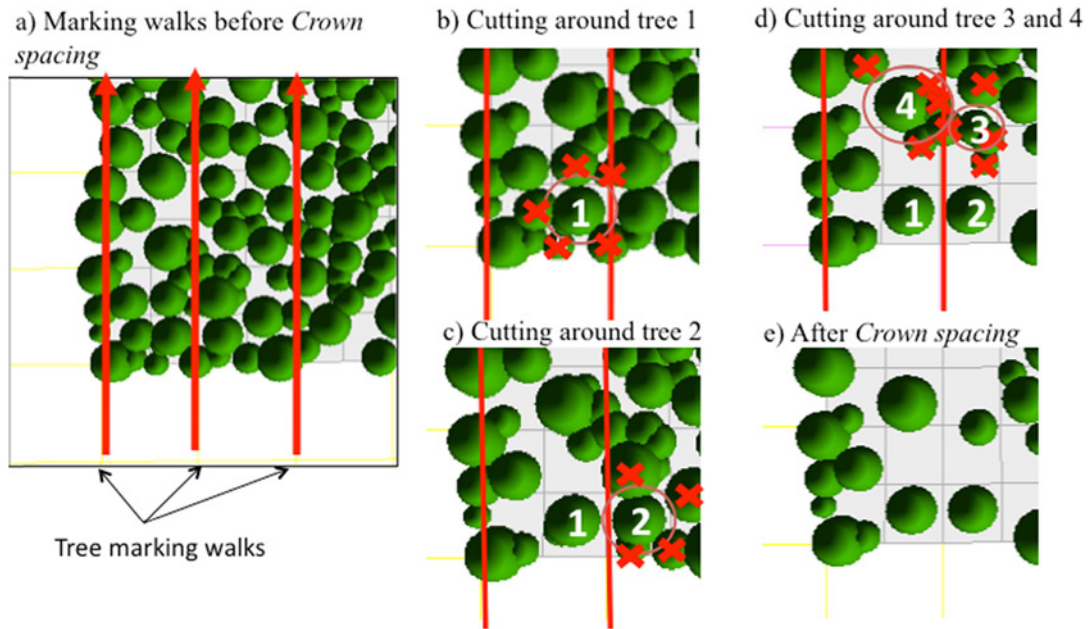


Fig. 4. Virtual tree marking walks used by FM to implement realistic *Crown-space* thinning at a distance D , which is the radius of red circles. Here, the sequence of *Plant* cutting occurring during the *Crown-Space* treatment is decomposed to illustrate the implemented algorithm.

costly, especially when the number of *Plants* and *LayerSets* gets very numerous. To be consistent with the fact that the spatial arrangement of the fuel heterogeneity inside each *LayerSet* is not defined until export via the *FuelMatrix* (described below in section 2.6), it is also not visualized in the 3D viewer. A couple of techniques are used to ease the computational burden of visualizing large numbers of plants. First, a degraded mode based on skeletons of *Plant* crowns is used by default during view manipulation (fast mode). Second, the rendering of *Plants* is modified and degraded when their number increases, so that *Scene* manipulation may still be maintained. Typically, when the number of *Plants* is smaller than 20,000, crowns and trunks are visualized but the number of sectors used for crown representation decreases from 16 to 4 proportionally with *Plant* number (decreasing the visualization quality setting from 100% to 50%). For a number of *Plants* between 20,000 and 150,000, the quality setting decreases from 50% to 1% such that the 4-sector crown representation is maintained only for a fraction of the tallest *Plants*, which decreases with *Plant* number. Above 150,000 *Plants*, all *Plants* are represented by their footprint only. The user can manually increase the quality setting for more accurate visualization and image capture.

2.6. Export to fire model using *FuelMatrix*

As a research fuel modeling platform, FM is ultimately intended to provide inputs for multiple fire models. At present, FM has been used most with FIRETEC. This three-dimensional two-phase transport model solves the conservation equations for mass, momentum, energy and chemical species (Linn and Cunningham, 2005) and simulates turbulent flows with Large-Eddy Simulation (LES, Pimont et al., 2009). FIRETEC fuel input data are four binary files that describe the spatial distribution of bulk density, water mass per volume, particle characteristic size and fuel height in each voxels of a 3D stretched computational grid. This information is computed by FM export for the entire *Scene* or any subdomain.

The export process uses a detailed structure, called the *FuelMatrix*, which divides each *Plant* or *LayerSet* into numerous small voxels, typically a tenth of the *Plant* size or *LayerSet* height. These

FuelMatrix voxels facilitates an explicit representation of the fuel distribution within individual *Plant* crowns and *LayerSets*. They allow objects to be accurately divided up among the larger voxels of the 3D grid that is used for the fire calculations. For FIRETEC, the computational grid spacing is typically on the order of 2 m in the x and y dimensions, and 1.5 m tall. An illustration of the export is shown in Fig. 5, where the *FuelMatrix* voxels associated each *Plant* and *LayerSet* are represented by red “small” boxes and the computational voxels of FIRETEC mesh are represented by black boxes.

The horizontal and vertical resolution of the *FuelMatrix* (i.e. the size of the small voxels) is set automatically according to item dimensions, but can be modified by the user. A finer resolution of *FuelMatrix* voxels will more accurately attribute fuel to fire simulation cells, but will correspondingly increase the computational burden for FM, increasing run time. The 3D viewer does not visualize spatial heterogeneity within *Plants* or *LayerSets*, such as the individual clumps corresponding to different *Layers*. However, *Layers* characteristics, such as cover fraction, clump size and spatial group, are used to generate spatial heterogeneities within the *LayerSet* which are represented explicitly to build the *FuelMatrix* (Fig. 5). The *FuelMatrix* contains all the relevant fuels information necessary for use with any physics-based fire model that we are aware of. More details are available in the online documentation.⁵

The FM is designed to support data intensive *Scenes* with significant numbers of *Plants* and large *LayerSets*. The *FuelMatrixes* of *Plants* and *LayerSets* are built one item at a time to avoid memory issues. The memory allocated to FM can also be increased depending on hardware capability (see online documentation). For large *LayerSets* that would require more memory than is allocated, FM can divide *LayerSets* into smaller triangular sections using recursive Delaunay triangulation. These innovations ensure that FM can continue to function even with very large data sets (e.g. section 3.1.3).

⁵ http://capsis.cirad.fr/capsis/help_en/capsis/lib/fire/exporter/firetec/firetecdialog.

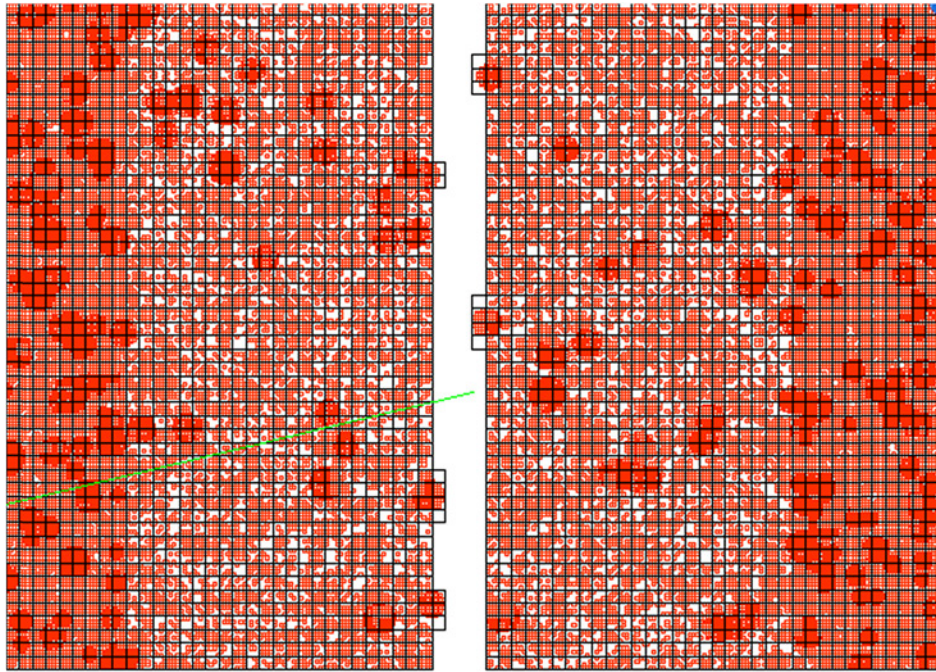


Fig. 5. Top view of the exported Scene presented in Fig. 13c. This is the scene presented in Fig. 3 after creation of a fuel-break. The small red boxes represent the voxels of the *FuelMatrices* that are not empty (Aleppo pine *Plants* and the kermes oak garrigue *LayerSets*). The horizontal spacing of these voxels is one tenth of *Plant* crown diameter for *Plants* and 0.25 m for *LayerSets*. The black boxes represent the FIRETEC computational grid (2 m resolution) to which *FuelMatrix* voxels are apportioned during export. Only the voxels (red and black) that contain fuel are represented and thus the road area has no fuel. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.7. Fire effects on plants

FM provides several approaches for representing or calculating fire effects (Fig. 6). For each *Plant*, fire effects are characterized by its *Severity*, that has several attributes describing *Plant* damage (damage to crown, trunk and bark) and *Status* (dead or alive, eventually mortality probability). *Damage* to crown and bole can be visualized in the 3D Editor/Viewer, whereas comparison between the

distribution of initial and killed *Plants* can be plotted in a graphic of the software by height classes.

FM has two distinctly different modes for fire-induced *Damage* to *Plants*. In the first, “observed” mode, the user has stem-mapped data for a real world fire or prescribed burn, and wishes to visualize their data using the sophisticated 3D visualization capabilities of FM. They may also have an interest in then carrying out subsequent simulations using that observed data as a starting point, for

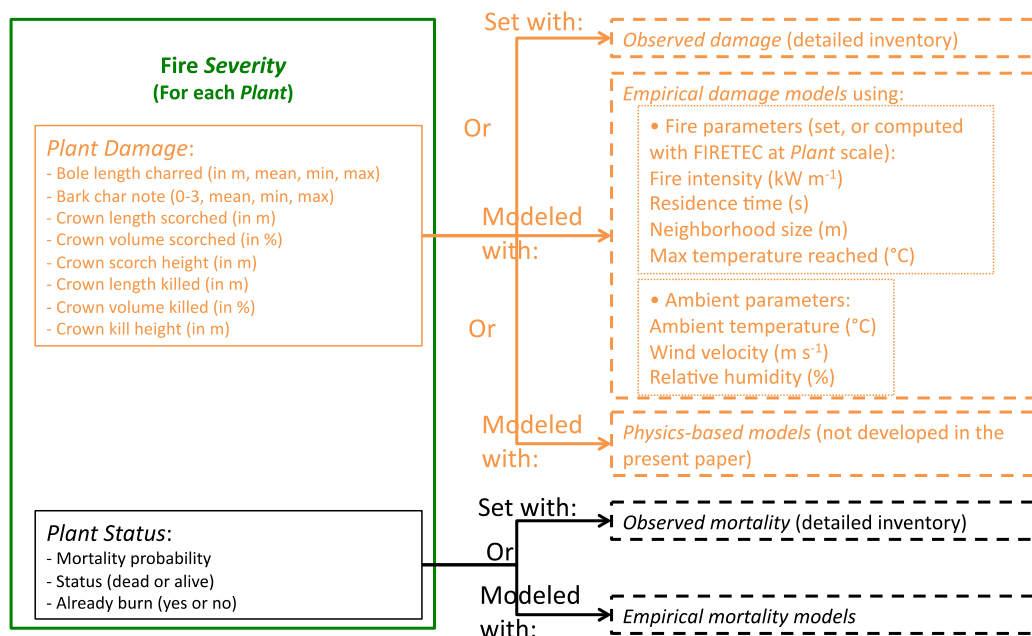


Fig. 6. Attributes and methods for Fire Severity of a *Plant*.

example to estimate post-fire mortality probability (*Plant Status* modeling described in the next paragraph). When not set as an input by the user from observed data, *Damage* can be computed for each *Plant* using empirical damage models. At present, several models are implemented (Van Wagner, 1973; Saveland and Neuenschwander, 1989; Finney and Martin, 1992; Michaletz and Johnson, 2006); with this approach, crown scorch is calculated as a function of ambient and fire parameters (fire intensity, wind velocity, ambient temperature, etc.), as well as lethal temperature. Two empirical models for cambium mortality assessment based on fire intensity and residence time are also implemented (Peterson and Ryan, 1986; Bova and Dickinson, 2005). In these models, bark thickness, a key required parameter, is computed in *FM* as a species-specific function of DBH. The fire behavior parameters (input data for *Damage* model) can be estimated with three different approaches. In the simplest approach, the user simply specifies a fire intensity level, which is applied uniformly across the entire domain. This approach is similar to that used in FFE-FVS (Reinhardt and Crookston, 2003). A more complex approach specifies a spread rate across the entire domain and uses Byram's formula (Byram, 1959) to compute local fire intensities around each tree as a function of the load available in its neighborhood. Finally, the most detailed approach employs the physics-based fire model FIRETEC to calculate fire intensity and residence time in the neighborhood of each tree.

Plant Status can be either “observed” (real world data) or computed, as a function of *Damage* (that can themselves be either observed or modeled). When modeled, *Plant Status* prediction is based on the computation of a post-fire mortality probability, using one of several logistic mortality models. These models are species-specific (models taken in Fernandes et al., 2008 and Pimont et al., 2011b for Mediterranean species), generic (Peterson and Ryan, 1986; Ryan and Amman, 1994) or biophysical (Michaletz and Johnson, 2008). There are few existing models for mortality for shrubs and other small plants, so at present, fire effects for collections of smaller plants such as are represented in *LayerSets* are limited to fuel consumption (when using the more complex FIRETEC approach).

Altogether, these various models offer several different options with regard to how fire effects are calculated for individual trees. *FM*'s capabilities to employ a wide range of fire effect models, as well as several options for how the fire itself is represented, together comprise a very useful platform for comparison of different approaches.

3. Application

Having described the basic components of the *FM*, we now describe some applications. We begin with a series of stand simulations illustrating the flexibility of the *FM* to model fuels from input data of different levels of detail. We then demonstrate applications involving fuel treatments, *Stand* dynamics and fire effects.

3.1. Flexibility to input data details

Available fuel data often vary widely in detail and form, from coarse descriptions and general characteristics as are common in many management situations, to stem-mapped stands with known spatial coordinates for each *Plant* as are typically only available after in-depth research data collection efforts. In the following paragraphs, we provide examples of how *FM* facilitates modeling fuels across this broad spectrum of input detail. All input formats shown below can be combined in a single file, thanks to a file loader that parses each format.

3.1.1. Modeling from coarse description: FireFlux experiment

The FireFlux experiment (Clements et al., 2007) fire behavior measurement study provides a good example in which fuels data were broadly characterized but not described in great detail. Dupuy et al. (2014) used *FM* to develop fuels inputs to simulate the experiments with FIRETEC. The experiment consisted of a fire in tall prairie grass fuels in the presence of detailed meteorological instruments. Available field data included ten fuel-loading and three fuel-moisture measurements in the grass fuels. Adjacent forested areas were not measured in the study. Although these forested areas were not part of the burn, they are important in model validation efforts because of their influence on the wind field. Dupuy et al. (2014) used the *LayerSet* approach to model both the grass and the forest canopies in the vicinity of the experiment. Example *LayerSet* parameters are presented in Table 1. The pattern and character of local forest, reconstructed through aerial imagery and conversations with the experiment participants after the experiment, is visualized in Fig. 7. The model-experiment comparison showed reasonable agreement (Dupuy et al., 2014). This example demonstrates that the *LayerSet* approach can be used to develop fuel characterizations from limited data that, despite their simplicity, are still useful for fire modeling purposes.

3.1.2. Modeled plant distribution

In this application, a large number of virtual stands were generated using *modeled plant distributions*, from commonly available stand characteristics (age, dominant height and stem density). Some quantities that require laborious sampling (canopy fuel load and single-sided LAI) were computed with *FM* for each *Stand* (Fig. 8). Given that such quantities are not readily available for managers, we used our modeled stands to investigate how they were related to more commonly available stand characteristics such as dominant height, basal area and cover fraction. An aerial visualization of one of the *Scene* is shown Fig. 14a. This application illustrates the benefit of the “script” mode, because 558 *Scenes* capturing a 16 ha Aleppo pine *Stand* were simulated, using observed stand characteristics collected by the French National Inventory (age, dominant height, number of stems per hectare) and the Aleppo pine distribution model (Appendix B). Aleppo pine *Plants* were modeled using equations provided in Appendix A and their spatial distribution was assessed with the modified “Hard core” algorithm described in section 2.3.

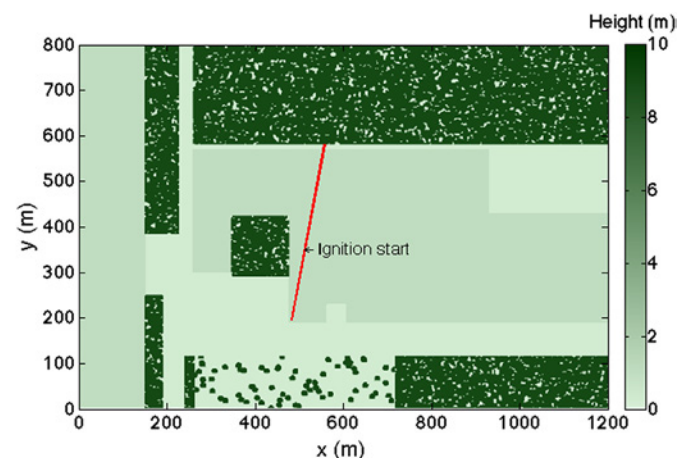


Fig. 7. Simulation domain and map of vegetation height for the FireFlux field experiment used in the evaluation of FIRETEC (Dupuy et al., 2014). The oblique orange line represents the ignition line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

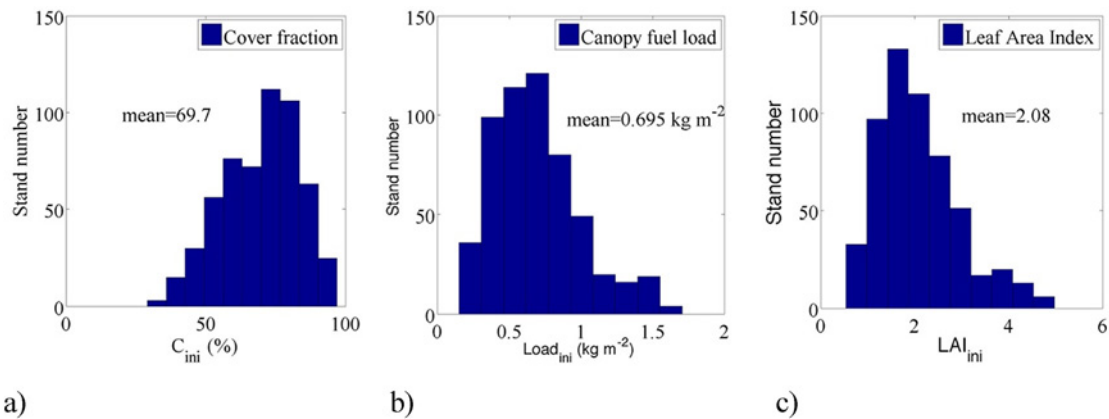


Fig. 8. Canopy fuel metric distributions for the 558 simulated *Stands*: (a) Cover fraction (C_{ini}); (b) Canopy fuel load ($Load_{ini}$); (c) Single-sided leaf area index (LAI_{ini}).

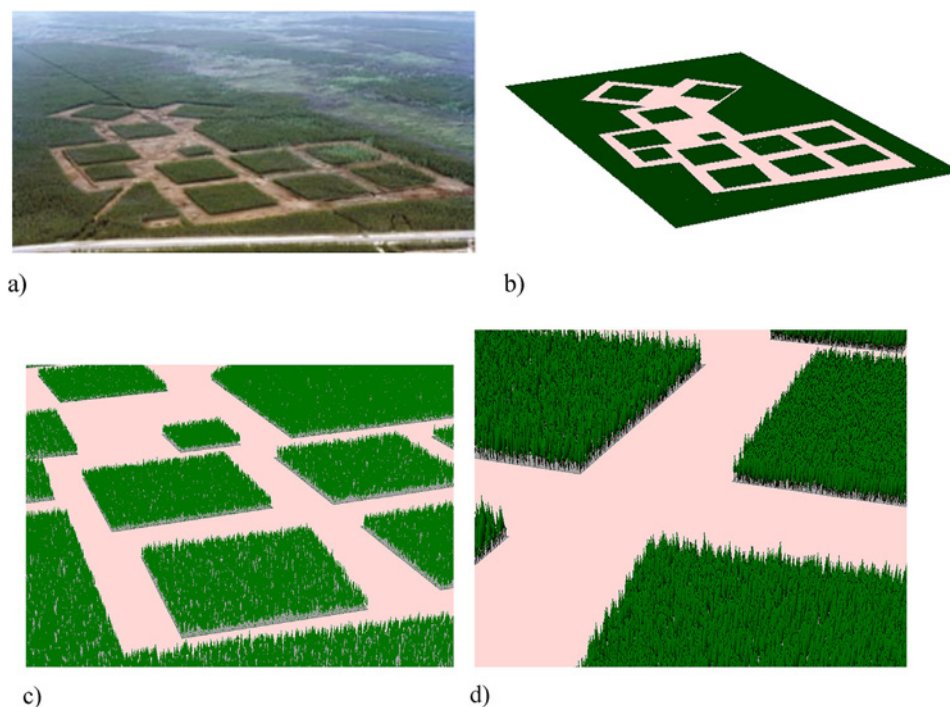


Fig. 9. Demonstration of *FM* visualization capabilities across a spectrum of spatial scales. (a) Photograph of ICFME experiment and (b, c, d) modeled aerial views of the same area, measuring $1700\text{ m} \times 1100\text{ m}$, with different levels of representational detail, specified with varying quality settings: (b) one million trees represented with 1% quality, as simple markers (dots) (c) Half of the tallest trees represented with 25% quality, as 3D tree crowns with 4 sectors; remaining plants represented as markers, and (d) 80%, all *Plants* rendered as 3D tree crowns with eleven sectors. In general, more sectors provide greater visual quality of the shape of the crowns.

Table 2 shows predictive models for canopy fuel load ($Load_{ini}$) and Leaf Area Index (LAI_{ini}) as a function of stand synthetic parameters such as canopy cover C_{ini} (%), dominant height H_{dom} and basal area BA_{ini} . Non-linear regressions were done using package *nlinfit* of MATLAB and Statistics Toolbox Release 2013b (The MathWorks, Inc., Massachusetts, United States). These predictive models are useful to managers because they provide a systematic method with which to predict important stand-scale fuel attributes based on easily-measured field characteristics.

3.1.3. Observed plant distribution: International crown fire modeling experiment (ICFME)

The ICFME is a good example of fire experiment in which fuels were described in details. It can be modeled with *FM* using *O. plant* distributions and *Plant* models. This crown fire experiment was

carried out during the late 1990's (Stocks et al., 2004). This field campaign was arguably the most instrumented crown fire experiments up to now and is still a key dataset for physic-based model evaluation. Four types of *Plants* were used to generate the fuel *Scene* (*Picea mariana* alive and dead, and *Pinus Banksiana*, alive and dead), using allometric equations to model *Plant* dimensions and for live and dead biomass of particles (leaves and 0–6 mm twigs). The vertical fuel distribution was modeled based on empirical vertical measurements for each *Particle* type (Alexander et al., 2004). 12 *Plant Stands* were modeled from their *Observed Plant* distribution of DBH (Alexander et al., 2004). Instead of using height classes, an allometric model for height, as a function of DBH, was derived from height and DBH classes. The *FM* was used to simulate the whole area of the ICFME (Fig. 9a, taken from Alexander et al., 2004). More than a million trees, represented as *Plants*, were modeled. With this

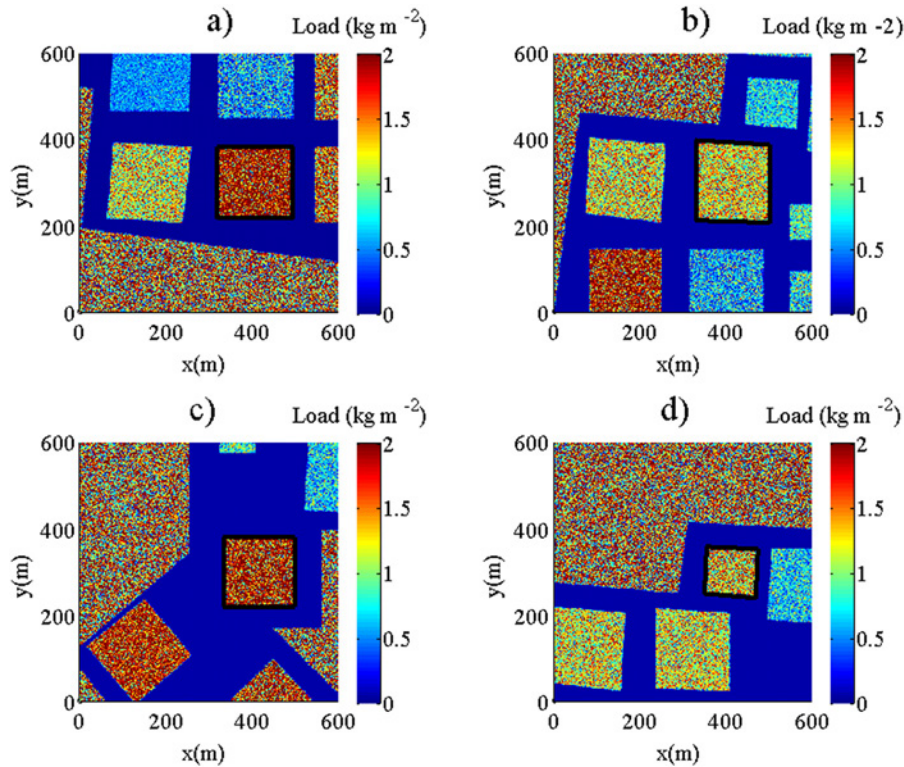


Fig. 10. Canopy load maps derived from the *Scene* build by *FM* and exported to FIRETEC input format. 'Plots' from Alexander et al. (2004) are delimited in thick black: (a) Plot 1; (b) Plot 4; (c) Plot 6; (d) Plot 9. Experimental wind comes from the left side of the plots.

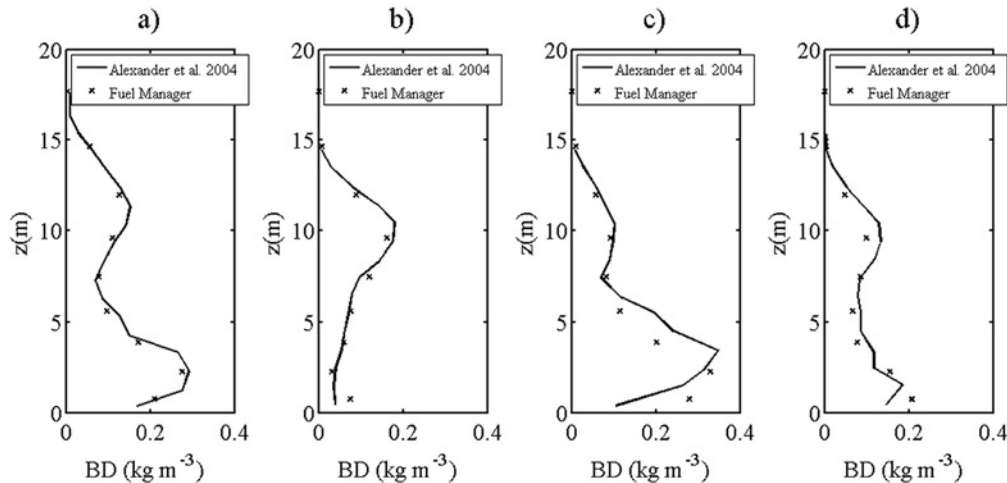


Fig. 11. Canopy bulk density (BD) profiles for 'Plots' reported in Alexander et al. (2004) and modeled with *FM* (from the *Scene* exported to FIRETEC input format): (a) Plot 1; (b) Plot 4; (c) Plot 6; (d) Plot 9. As reported by Linn et al. (2012), Plot 6 and 7 were inverted in Fig. 12 from Alexander et al. (2004) and this was corrected here.

many objects it is impractical for most purposes to represent them as 3D objects, so they are instead represented as markers, or simple dots, indicating their locations. Fig. 9 illustrates different levels of detail, set by the user with quality settings.

Pimont et al. (2014) used *FM* to create input data for FIRETEC with *FM* for 4 selected plots to compare predictions of fire behavior and radiant fluxes with experimental values. Among these input data, tridimensional bulk density arrays were used to compute fuel maps (Fig. 10) and *Stand* bulk density profiles (Fig. 11, crosses). Following Alexander et al. (2004), *Stands* are called 'Plots' and the profiles reported their Fig. 12 are shown (lines). Agreement

between the two datasets is generally very good ($RMSE = 0.0306 \text{ kg m}^{-3}$, computed after interpolation of Alexander's data on FIRETEC vertical grid), illustrating the accuracy of the modeling approach. The few minor differences between the profiles, however, are readily explained. First, vertical classes are not the same (1 m for Alexander et al. (2004) vs. stretched grid of FIRETEC for *FM* data with cell heights close to 1.5 m). Second, Alexander et al. (2004) included woody fuels of up to 1 cm in diameter, whereas FIRETEC input data were limited to 6 mm, a threshold commonly used for fine fuels. Third, in *FM*, the bulk density at 0.75 m height above the ground includes both canopy

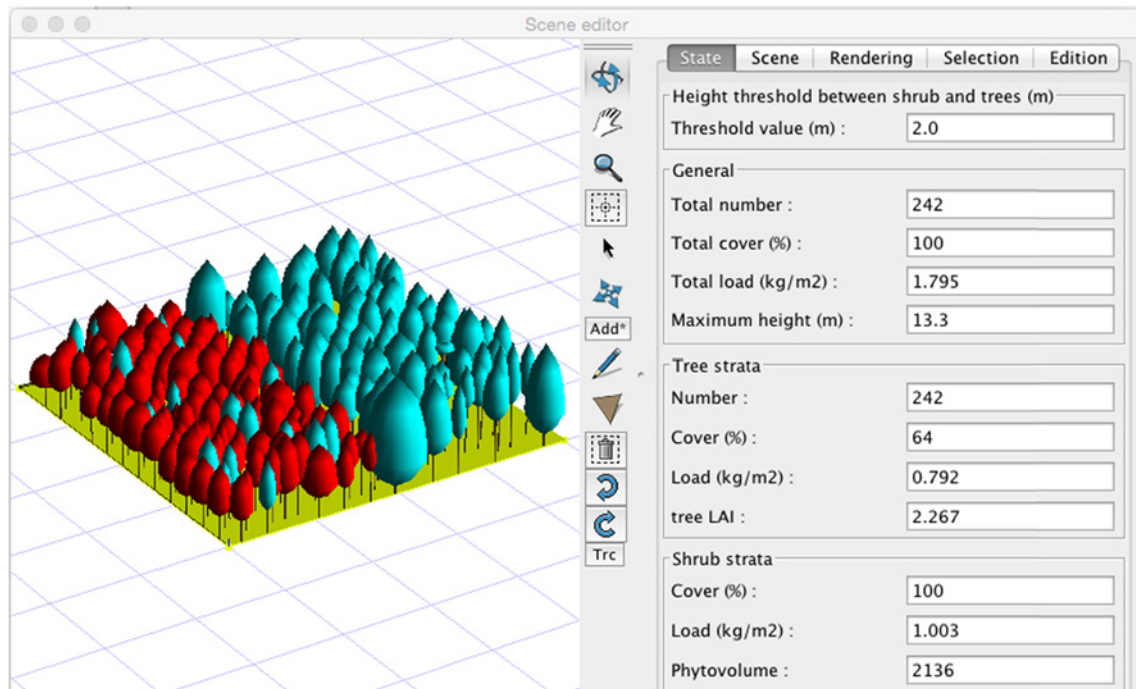


Fig. 12. Visualization of the mixed Aleppo (blue) and Stone pine (red) fire experiment.

and surface fuel loads, whereas Alexander et al. (2004)'s Fig. 12 showed canopy fuels only. Finally, FM used DBH classes and an allometric relation between DBH and height, instead of combining DBH and H classes as in Alexander et al. (2004), resulting in small differences in biomass allocation (especially visible in Plot 6).

3.1.4. Stem-mapped data: mixed Aleppo and Stone pine fire experiment

The greatest level of details regarding fuel description is achieved when a stem map is built. To describe the fuel of a fire experiment carried out in July 2011 in a 40 × 40 m mixed Aleppo and Stone pine (*Pinus pinea* L.) plantation of 16 years old (close to Avignon, France, Rigolot et al., 2014), the location, DBH, height, crown base height, crown diameter of each species were measured. An artificial understory of uniformly spread straw was added to ensure a continuous medium–high intensity fire. This dataset was used to parameterize the fuel scene in the FM, using the Plant inventory description for trees and a homogeneous LayerSet for the understory (Fig. 12). Some applications of FM's fire-effect package are described in section 3.2.3.

3.2. Simulating fuel treatments, stand dynamics and fire effects

In this section, we show how the initial Scenes (generated from various input data in the previous section) can be modified under various scenarios, including fuel treatments, growth over time and fire events.

3.2.1. General framework

As a module within the larger CAPSIS forestry modeling framework (Dufour-Kowalski et al., 2012), FM benefits from the CAPSIS architecture in its powerful and flexible approach for modeling vegetation change over time, both through growth and succession, as well as for changes arising from management actions such as fuel treatments. The model architecture provides a means of developing an “event tree” in which an initial Scene serves as the

starting point for a series of different potential sequential events (Steps). Any point in the sequence can then serve as the starting point for branching stages leading to multiple potential subsequent evolution paths. This approach allows direct comparison of different complex alternative states that depend on various sequences of possible events. An example of this “event tree” is shown in Fig. 13a, with three different scenarios (including a fire), as well as visualization of the Scene at the end of each scenario (Fig. 13b, c and d). The growth over time for individual Plants (Aleppo pine) is computed (Stand Dynamics, Dreyfus et al., 2001), while a Succession Model is used for the LayerSets, using the Kermes oak understory model presented in Appendix C. Using the fire-effect package (section 2.7), fire effects were computed using empirical models of fire damage to crown, bole and bark and also specific or generic logistic models for tree mortality, assuming for demonstration a prescribed fire spreading at 0.05 ms⁻¹ with a residence time of 60 s, a 2 ms⁻¹ wind and a 15 °C ambient temperature. Damage to crown and bole, as well as mortality distribution are plotted in Fig. 13c and d.

3.2.2. Fuel treatment example with crown-space thinning

Here, we applied crown-space thinning to the 558 simulated plots described in section 3.1.2. FM was used to investigate how post-thinning stand characteristics (load, LAI, cover fraction, etc.) relate with common stand characteristics and thinning intensity. Thinning scenarios were simulated using the thinning algorithm described in section 2.5, with a target crown space D, varying from 1 to 10 m (Fig. 14b and c). These 6138 simulations (558 × 11) approximately took 24 h on standard desk computer using script mode.

Simulation outputs were used to develop statistical models as function of stand characteristics and crown-space (D), to predict post-treatment canopy loads (Load), canopy cover fraction (C), Leaf Area Index (LAI), numbers of stems per hectare (N) and basal areas (BA). Equations are provided in Table 2. These simple operational models provide managers a useful application of stand modeling,

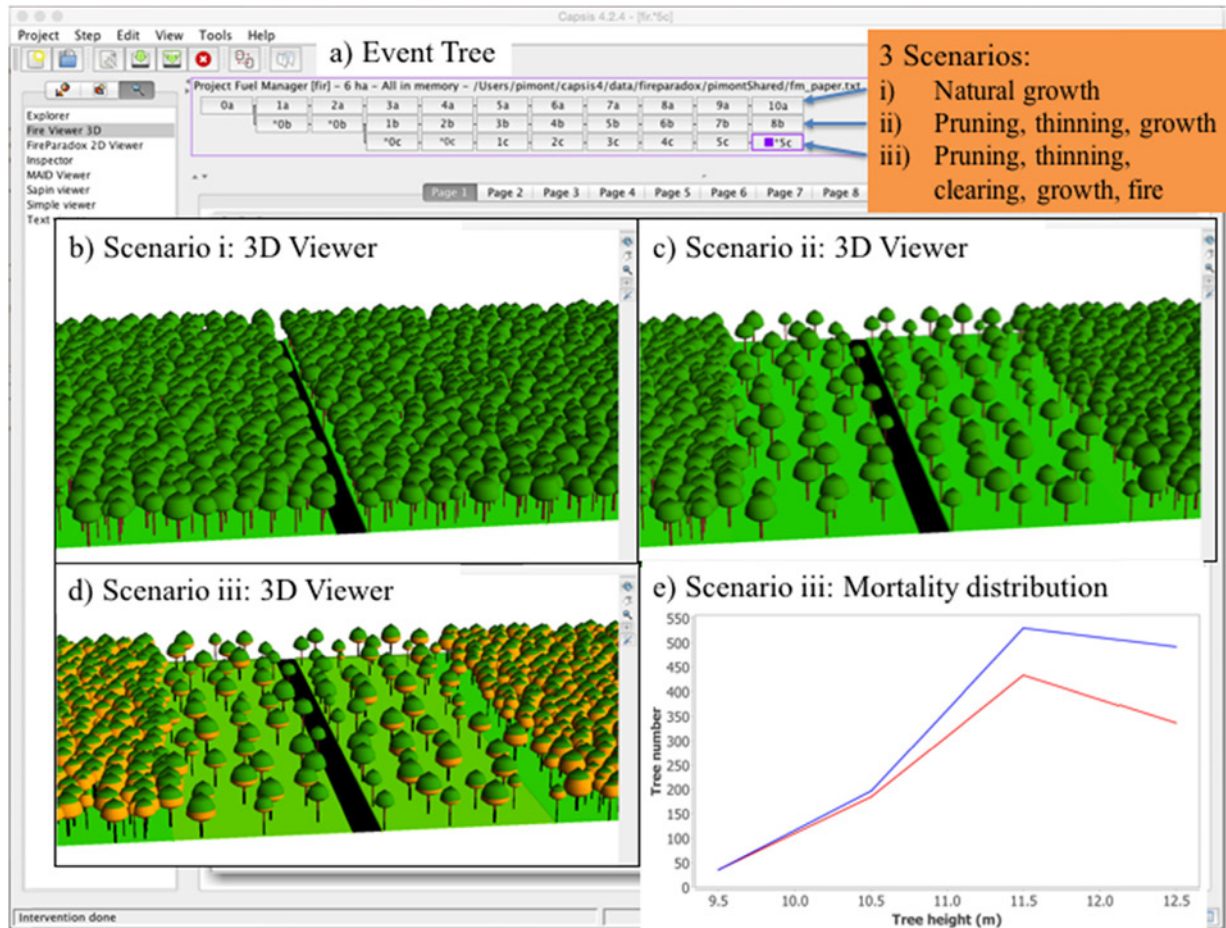


Fig. 13. View of the FM graphical interface illustrating Aleppo pine stands separated by a forest road (shown in black). (a) The “Event Tree” represents change over time as a series of branching events (Steps, represented by labeled rectangles) that could occur in each scenario, starting from a single initial Step (0a); (b) Visualization of Scenario i): Natural growth over time for ten years; (c) Visualization of Scenario ii): Crown-space thinning (5 m between crowns) and pruning (5 m above ground) on a 100 m wide zone and LayerSet clearing, followed by eight years of growth; (d) Visualization of Scenario iii): Same crown-space thinning and pruning as ii), and LayerSet clearing on the 100 m wide zone, followed by three years of growth and a fire spreading at 0.05 ms^{-1} ; The visualization includes fire damage representation (crown scorch in orange and charred boles in black); (e) Fire induced mortality for scenario iii) (in red), compared to their original number (in blue), by height classes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

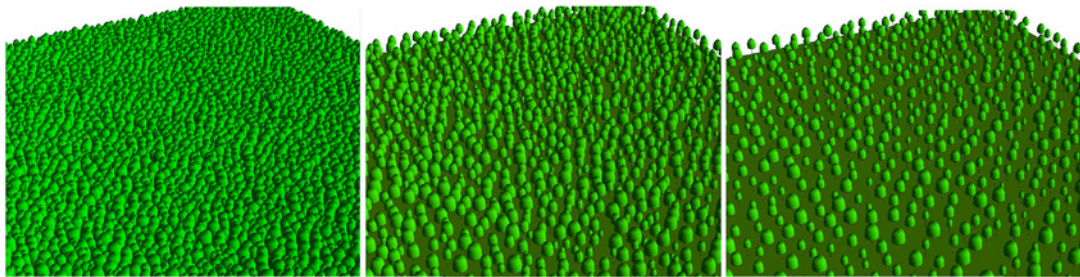


Fig. 14. Simulation of a 50 year-old Aleppo pine Stand, with a 12 m dominant height: (a) Initial Stand before ($700 \text{ stems ha}^{-1}$); (b) Stand after crown-space thinning ($D = 2 \text{ m}$); (c) Stand after crown-space thinning ($D = 5 \text{ m}$).

allowing fuel characteristics of Aleppo pine stands to be estimated according to thinning intensity.

3.2.3. Application to the mixed Aleppo-Stone pine fire experiment

This fire-effect package was applied to the experimental fire associated with the fuel described in section 3.1.4. The mean spread rate was 0.18 m s^{-1} . The fire weather conditions were severe with a Fire Weather Index (Stocks et al., 1989) greater than 100. The air

was dry (30%) and hot (27°C) and the wind was strong (15 m s^{-1} at 10 m height) with 20 ms^{-1} gusts. Immediate fire effects on pines were measured using both crown and bole damage indicators. These observed fire effects can be seen either on Fig. 15a (photographs) or 15b (visualizations created with FM 3D viewer based on measured damage). Assuming constant spread rate over the plot, Byram's fire intensity was computed and used to simulate crown scorch, using Van Wagner scorch model (Fig. 15c), even if not

Table 2

Equations derived from the 558 simulated *Scenes*: initial *Scenes* before thinning (section 3.1.2) and modified after various *crown-space* thinning (section 3.2.2). The equations assess the relationships between easily-measured stand attributes and fuels attributes that are critical, but difficult to measure directly.

Modeled quantity	Fuel treatment	Model	R ²	RMSE
Load _{ini} (kg m ⁻²)	Before thinning	$(0.00637 + 0.00809 H_{dom})e^{0.0271C_{ini}}$	0.954	0.0639
Load _{ini} (kg m ⁻²)	Before thinning	$0.0402 BA_{ini}$	0.990	0.00781
LAI _{ini}	Before thinning	$(0.0672 + 0.0191 H_{dom})e^{0.0276C_{ini}}$	0.940	0.208
Load (kg m ⁻²)	After thinning	$0.0637 \left(\frac{H_{dom}}{1.95+D} \right)^{1.22}$	0.880	0.0368
LAI	After thinning	$0.1839 \left(\frac{H_{dom}}{1.23+D} \right)^{1.03}$	0.927	0.0792
C (%)	After thinning	$\frac{29.9 C_{ini}^{0.425}}{(2.10+D)^{1.31}}$	0.901	3.54
BA (m ² ha ⁻¹)	After thinning	$\frac{70.6 BA_{ini}^{0.74}}{(2.00+D)^{1.31}}$	0.976	0.422
N (ha ⁻¹)	After thinning	$\frac{50.7 N_{ini}^{0.469}}{(1.84+D)^{1.31}}$	0.909	24.1

BA_{ini}/BA: basal area before/after thinning (m² ha⁻¹); C_{ini}/C: Cover fraction before/after thinning; D: between tree crown spacing (m) for crown-space thinning; H_{dom}: Dominant height (m); N_{ini}/N: Number of stem per ha before/after thinning.

designed to be used with strong winds. The fire behavior was in reality highly heterogeneous, spreading mostly downwind in the right part of the plot and flanking or backing in the left part of the plot, so that the constant spread rate assumption led to a bad prediction with Van Wagner model.

FM was used to plot the initial (blue) and killed (red) *Plant* distribution for Aleppo and Stone pines (Fig. 16). Observed distributions plotted in Fig. 16a and b shows that mortality was large among Aleppo pines, whereas all Stone pines survived. Using empirical mortality models, the *FM* computed the distributions of killed *Plant* and they compared favorably with observations (Fig. 16 c and d). The success in predictions (hits and rejects) was about 80% for Aleppo pine and 90% for Stone pine (Rigolot et al., 2014). The *FM* also computed killed *Plant* distribution using modeled damage (assuming constant spread rate and using Van Wagner model, as above). Aleppo pine mortality was largely underestimated (Fig. 16e), whereas Stone pine survival was well predicted (Fig. 16f). This simple example illustrates that accurate predictions of local fire behavior are critical to correctly model *Plant* damage and mortality.

3.3. Other applications

Beyond the examples of applications shown above, *FM* has been used in a number of studies examining different aspects of fire behavior, including the effects of prescribed burning as a fuel treatment (Cassagne et al., 2011) and assessing changes in fire behavior arising from a fuel-break (Pimont et al., 2014). Although *FM* has many capabilities for forest environments, it has also been used to investigate fire behavior in shrublands: sensitivity to fuel moisture and bulk density (Marino et al., 2012), influence of topography and fire front width (Pimont et al., 2012), and backfire simulations (Dupuy et al., 2011).

4. Discussion

The multiple applications shown or cited above demonstrate that *FM* is a powerful and flexible tool in the context of fuel modeling. The *Plant* and *LayerSet* modeling approaches, used both individually and collectively, provide considerable flexibility in representing natural and managed fuels and thus make it possible to represent nearly any fuel scenario desired. Due to an efficient data structure, the model can simulate and represent large *Scenes* with many fuel items quite quickly. The system is similarly flexible to a wide range of input formats and levels of data detail, from coarse to very detailed (section 3.1). One of the most important

applications of *FM* is to provide input to physics-based fire models such as FIRETEC. Although we have not demonstrated it in this paper, we have recently developed export procedures in *FM* to provide input to a different physics-based fire model, WFDS (Mell et al., 2009). The capability to provide detailed fuels data to both FIRETEC and WFDS will open the door for robust cross-model comparisons, evaluation of individual model components and algorithms, and numerical approaches.

While providing input data for physical fire model simulations is certainly a central purpose of the software, *FM* is not simply an appendage to the fire models. The capabilities of *FM* to quantify and visualize fuel characteristics, as well as fuel changes resulting from growth over time or fuel treatments, demonstrate the value of the model in its own right. In this context, the script mode is especially important to automate calculations for a large number of fuel scenarios. This capability is one of the many important features, which derive from the underlying CAPSIS modeling platform. Integration with the CAPSIS platform is greatly beneficial because the shared architecture between *FM* and numerous other models implemented in CAPSIS offers a straightforward means of collaborating with other modelers, incorporating components from other models or for testing different algorithms for similar purposes. The nature of the CAPSIS-based collaboration is itself a benefit because it provides significant core support from the developers within the CAPSIS project.

Many commonly-used fire models, such as FARSITE (Finney, 2004), consider fuels at stand scales as homogeneous, while in reality fuels are typically quite variable, both in structure and composition (Sikkink and Keane, 2008) as well as in spatial pattern (Keane et al., 2012). One key aspect of *FM* that sets it apart from other software used for similar purposes, such as FFE-FVS (Crookston and Dixon, 2005) or ArcFuels (Ager et al., 2012), is the spatially-explicit representation of fuels within a forested stand. Both FFE-FVS and ArcFuels use individual tree data, and are capable, through the FVS model, of predicting tree growth and quantifying certain changes in fuels following a fuel treatment. However, there is little capability within these modeling frameworks to assess the spatially-explicit effect of fuel changes at the scale at which fuels are actually manipulated – within a stand. Thus, two stands with the same set of trees but different spatial configurations would have identical results with these models, whereas in reality, and in the context of *FM*, the spatial arrangement of the trees could significantly affect fire behavior outcomes. *FM* enables to strictly control stochasticity thanks to the use of random seeds. This feature enables the user to generate replicates of a given configuration for sensitivity analysis. The capabilities of *FM* to represent fuel

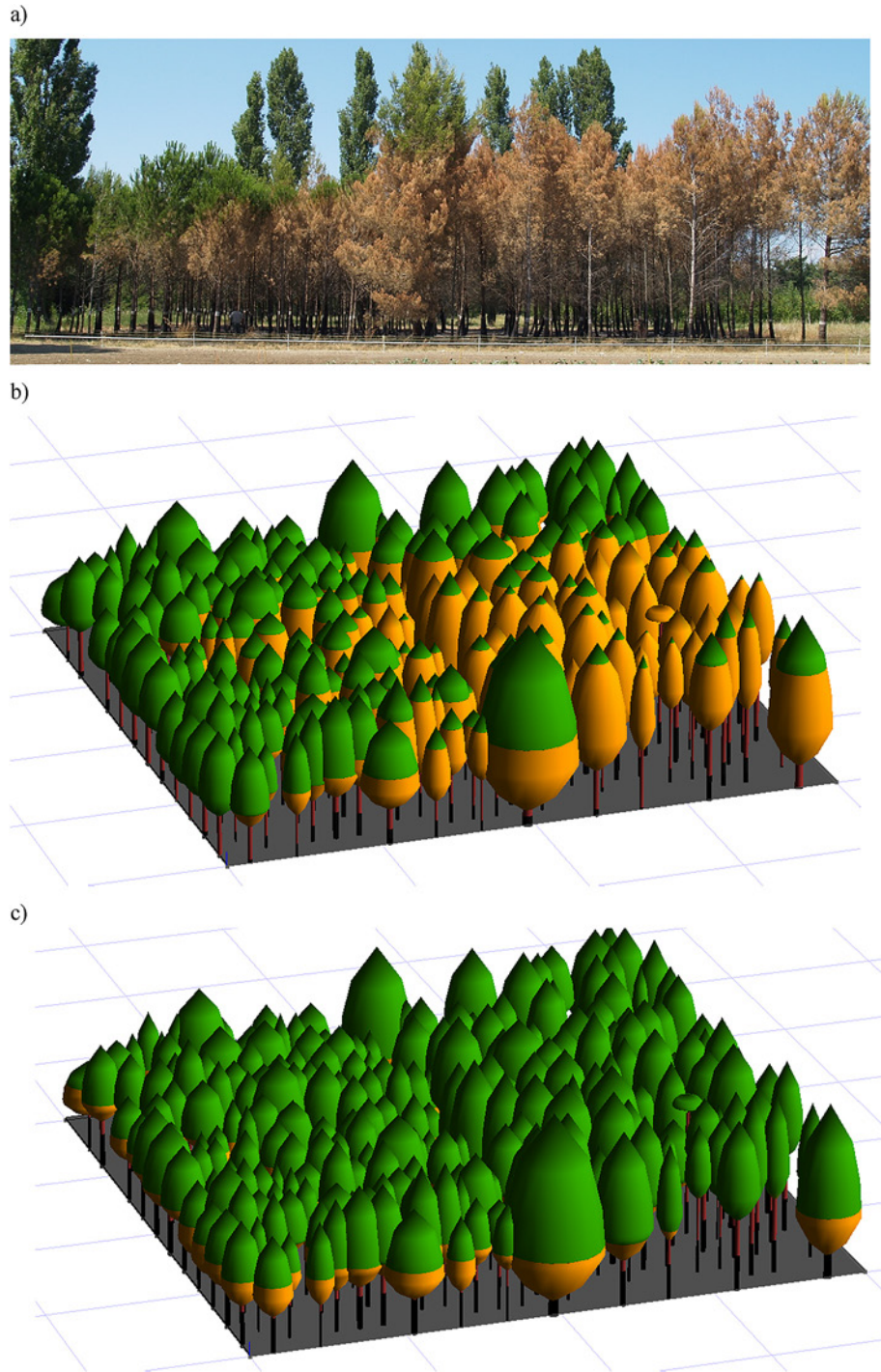


Fig. 15. Crown and bole damage after Les Vignères fire experiment: (a) Photograph (Left, Stone pines; Right, Aleppo pines); (b) Observed data, visualized with the 3D Viewer; (c) Predicted data, visualized with the 3D Viewer, assuming constant spread rate in *Stand* and using Van Wagner model.

heterogeneity, and provide detailed data as input to two independently developed physics-based fire models has significant implications for fuel management and for other natural resource concerns. For example, millions of acres of forest are considered to require fuel management in the United States (GAO, 2006), but specific guidelines regarding tree spacing to reliably modify fire behavior are still uncertain. In many areas, habitat requirements for threatened or endangered species dictate desirable forest structure characteristics (Squires and Ruggiero, 1996; Reich et al., 2004), but

there are few tools at present for assessing and potentially mitigating conflicts between habitat maintenance and fuel management objectives. Use of *FM* in conjunction with fire models such as FIRETEC or WFDS provide a means of examining and possibly mitigating such issues. To our knowledge, *FM* is the first model that provides the necessary suite of capabilities to serve this purpose.

While *FM* is promising in many ways, many challenges remain that must be addressed before the complete potential of detailed fuel and fire modeling efforts can be fully realized. Challenges arise

with respect to fuels, fire and fire-effects modeling. Only thirteen species (mostly European fire prone species) are represented in the *FM* at present. However, users can easily develop simple *Plant* models for other species without additional coding, since pre-defined equations and parameters can be defined in a separate text file (*speciesFile*⁶) and crown dimension, biomass equations or distribution are often available in literature. We are currently engaged in efforts to expand these modeling capabilities to a much larger set of species and ecosystems through the STANDFIRE module, developed on the same basis as *FM* in the CAPSIS platform, which builds connections to the US system FFE-FVS, which is widely used in the United States to facilitate fuel modeling throughout the United States. This module will be described in greater detail in subsequent publications.

Fuel modeling efforts rely heavily on allometric equations to provide biomass estimates. Although this issue is not specific to *FM*, the accuracy of allometric equations used for biomass computation and defining spatial distributions can in some cases be an issue. In order to be robust, allometric equations require significant sampling since the finer diameter biomass components most significant to fire do not only vary with stem diameter, but also with crown dimension, competition, stand age, basal area, management practices and even day in the year (Baldwin et al., 1997; Monserud and Marshall, 1999; Shaiek et al., 2011). Sensitivity to the type of equation used for vertical distribution may also be high (Baldwin et al., 1997). Novel promising techniques for detailed fuel mapping such as terrestrial LiDAR (Seielstad et al., 2011; Skowronski et al., 2011; Pimont et al., 2015) can be used to augment and refine allometric equations. These approaches will have to be integrated as additional input formats in *FM* or STANDFIRE in the future. Of particular concern in an era of climate change is that many biomass equations are built upon data collected under climatic conditions that may not be representative of current or future conditions. Similarly, many fuel characteristics relevant to fire behavior are affected by environmental conditions, evolving under climate change (Moreno, 2009; Sabaté and Gracia, 2011). Efforts will be made to link biomass and moisture estimates more explicitly to environmental conditions and climate change projections using plant functional models, to ensure continued relevance and appropriate sensitivity to these important drivers.

Challenges arise in fire behavior modeling as well. The use of physics-based fire models is a rapidly growing field, and has promise for providing insights useful to many contemporary fire and fuel questions due to the greater detail with which fuel information can be used and the advantages of mechanistic process modeling in physics-based models. Previous simulation efforts have illustrated that these models produce outcomes that compare favorably with observed data (Linn and Cunninham, 2005; Mell et al., 2007; Pimont et al., 2009, 2014; Linn et al., 2012; Dupuy et al., 2014; Mueller et al., 2014; Hoffman et al., 2015b). However, as a relatively recent research arena, many aspects of this field are still the subjects of active investigation, and further refinements will likely result over time.

To identify strengths and weaknesses of physics-based wildfire models and address concerns about the use of these models (Alexander and Cruz, 2013), ongoing validation efforts will be critical to explore a broad range of fire regimes. A part of such validation efforts will be assessing the sensitivity of simulation output, and potentially the measured fire behavior by proxy, to many different aspects of simulation inputs including initial and boundary conditions, numerical spatial and temporal resolution, and broad range atmospheric conditions. Due to its influence on

both fire behavior and on the winds that most affect the fire, adequate representation of the vegetation is a crucial aspect of the specified environmental conditions. New validation efforts will be carried out as new data becomes available, but recent studies have shown that careful attention must be paid to the heterogeneous nature of the fuels and to the dynamic nature of the ambient wind fields surrounding the observed fire. Vegetation structure determines the continuity of the fuels and the amount of material that is present to burn, but it also influences the wind velocities within the canopy, which can be a major source of uncertainty (Linn et al., 2012) and often exhibit significant spatial and temporal variability (Cruz and Alexander, 2013). With its ability to develop ensemble fuel arrangements consistent with landscape-scale measurements, the *FM* can play an important role in evaluating the sensitivity of model results and maybe even fire behavior to various degrees of changes in fuel arrangements. This is key since this type of vegetation specification is seldom documented even for detailed experiments. The use of *FM* will increase the robustness of fire modeling studies, since it allows to build input data in a transparent and reproducible manner.

Predicting fire effects on soils and vegetation is key to understanding fire's role in landscape evolution and the potential long-term impacts of fuels management. Unfortunately, until now, only limited agreement between predictions and reality (Karau and Keane, 2010) has been achieved. The two most significant reasons for the disagreement cited by these authors are 1) not accounting for the differences in the physics associated with various forms of fire propagation (head, flanking or backing fire) and 2) not capturing the fine-scale heterogeneity of fire damage related to variations in local fire behavior such as those that lead to heterogeneous scorch heights. Without accounting for the physical processes such as the convective heat transfer and oxygen depletion that lead to differences between modes of fire spread and such heterogeneity, it is difficult to account for even the scorch levels. This is illustrated by the small fire effect experiment reported in section 3.2.3, where mortality models provided satisfactory prediction when using observed damage, but performed poorly when used with modeled damage, since fire behavior was far from being homogeneous at plot scale. The heterogeneity of the processes and the complex fire environments make it difficult to achieve cross-cutting empirical relations. For example, even when the formulation is the same among empirical crown scorch models (they use the same function of fire intensity derived from plume theory multiplied by various constants), the constants vary significantly among studies, from 2.7 in Saveland and Neyenschwander (1989) to 4.6 in Van Wagner (1973) (the first crown-scorch model) to 8.9 in Finney and Martin (1992). Due to their process-based formulations, physics-based models have the potential to provide new opportunities to develop fire intensity and residence time maps, so that predictions of fire damage would be more accurate. Physics-based model formulations attempt to represent the critical processes that drive fire behavior, but these are also the same processes that lead to the heterogeneous effects. Some preliminary explorations have provided encouraging ability to simulate key effects drivers such as convective fluxes, which compare favorably to measurements (Dupuy et al., 2014). Connecting such physical processes or drivers to fire effects requires linking the fire models to biophysical models that are capable of determining heterogeneous fire effects over the landscape and throughout the canopy. The different steps required to link biophysical models of fire effects (Jones et al., 2004, 2006; Dickinson and Johnson, 2004; Michaletz and Johnson, 2006) have been implemented in *FM* (input, output, models, etc.). However, these developments, while very promising, are beyond the scope of the present paper and require additional testing and validation.

⁶ http://capsis.cirad.fr/capsis/help_en/firelib/speciesfile.

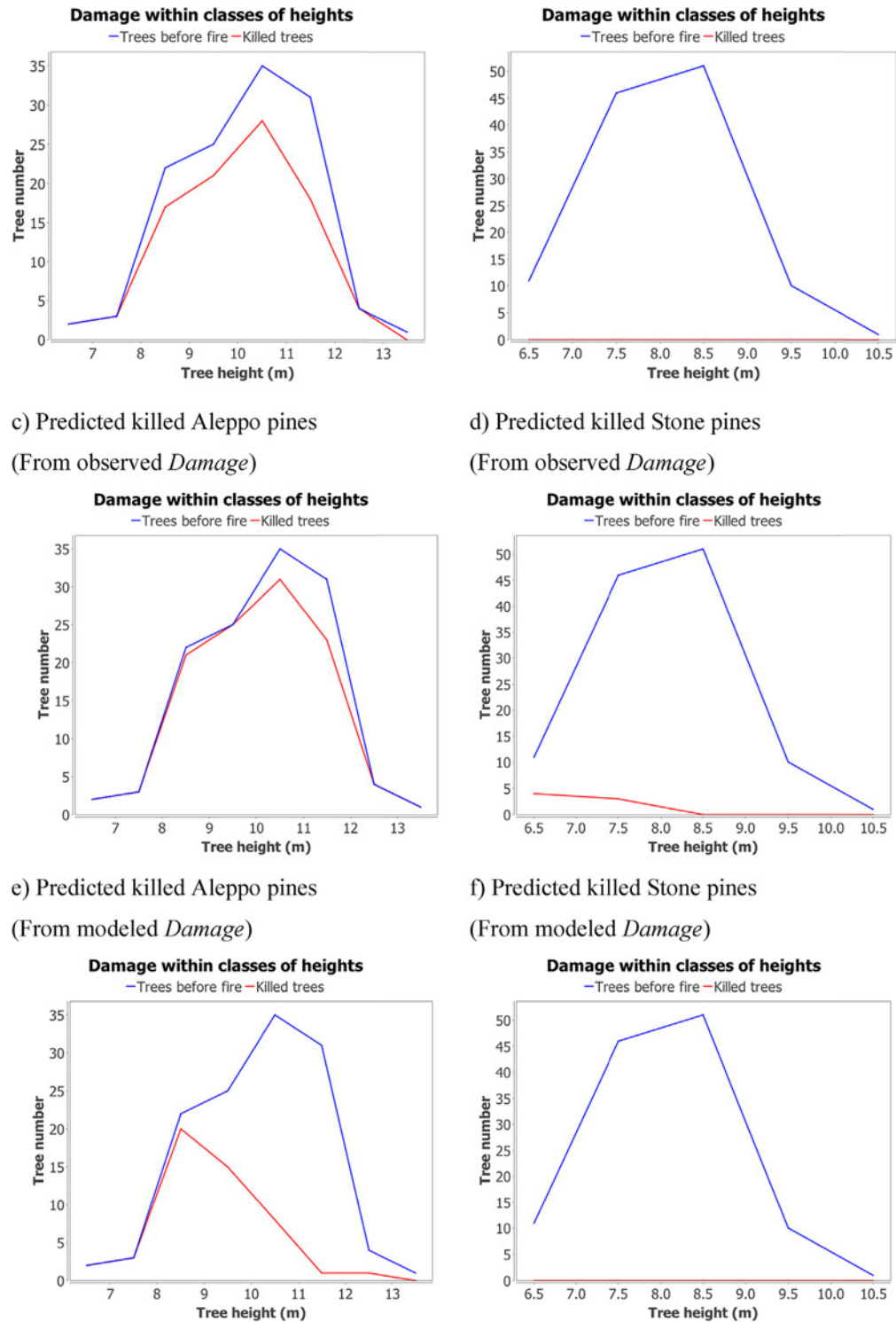


Fig. 16. Initial (blue) and killed (red) *Plant* distribution for Aleppo and Stone pines: (a, b) Observed; (c, d) Predicted from observed damage, using empirical mortality models; (e, f) Predicted from modeled damage, assuming constant surface fire spread rate in *Stand* and using Byram's intensity, Van Wagner crown damage model and empirical mortality models. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5. Conclusion

In this paper, we have described and demonstrated the capabilities of FuelManager, a software used to model and quantify wildland fuels. FuelManager provides detailed fuels inputs for the physics-based fire model, FIRETEC, as well as several applications

exploring how fuel management efforts may affect fire behavior. FuelManager integrates a wide range of fuel modeling capabilities, numerous recent fire-effect research results and recent technologies for visualization and *Scene* manipulation to provide a broad suite of capabilities relevant to examinations of fuel management scenarios. While challenges in fuel, fire behavior and fire-effect

modeling remain, the capabilities of *FM* significantly increase our ability to examine relationships between fuels in a wide variety of settings, fire behavior and fire effects. These developments lead to a more robust understanding of wildland fire science, which, in a future predicted with climate change to have increasing fire frequency and severity in many areas, will be increasingly important over time. We recognize, however, that further developments in wildland fire science will take place over time. We hope that, as an evolving fuel modeling platform, that new developments in wildland fuels science will be incorporated into FuelManager and/or STANDFIRE as time goes on.

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Appendix A. Aleppo pine Plant model

Table A1
Main equations used for the *Pinus halepensis* Plant model.

Quantity	Model	Reference
H (m)	$1.3 + \left(1.01 \left(\frac{1}{DBH} - \frac{1}{D_{dom}}\right) + \left(\frac{1}{H_{dom} - 1.3}\right)^{1/3}\right)^{-3}$	Dreyfus et al., 2001; Dreyfus, 2012
CD (m)	$\frac{2H}{\exp(0.668 + 1.73 \exp(-15800 HD^{-2.5} - 0.0035\pi DBH))}$ (with $HD = \frac{H-1.3}{0.01DBH}$)	Dreyfus, unpublished data
CBH (m)	$\frac{H}{\exp(DH(2.15 + 1900/AGE))}$ (with $DH = \frac{0.01DBH}{H}$)	Dreyfus et al., 2001
Biomass (kg)	Needles: $0.026 DBH^{1.93}$ Live 0–6 mm twigs: $0.00546 DBH^{2.13}$ Dead 0–6 mm twigs: $0.000360 DBH^{2.62}$	Mitsopoulos and Dimitrakopoulos, 2007a,b; Lopez-Serrano et al., 2000; Lopez-Serrano et al., 2005
Cumulative biomass distribution	$\frac{1.05}{1 + \exp(4.93 - 8.06 z/H)}$ (z being the height in crown, m)	Mitsopoulos and Dimitrakopoulos, 2007a

AGE: Tree age (in year); CBH: Crown base height (m); CD: Crown diameter (m); DBH: Diameter at breast height (cm); D_{dom} : Dominant diameter of a *Plant Stand* (cm); H: Height (m); H_{dom} : Dominant height of a *Plant Stand* (m).

Appendix B. Aleppo pine DBH distribution Model

A three-parameter Weibull distribution shape was used to model DBH distributions from three synthetic stand characteristics: AGE, site index (dominant height at the age of 50 years, H_{dom}^{50}) and number of stems per hectare (N).

The dominant height (in m) as a function of age and site index was given by (Couhert and Duplat, 1993):

$$H_{dom} = 0.3 + 2.01 \left(H_{dom}^{50} - 0.3 \right) \times \left(1 - \exp \left(-0.366 (AGE - 5)^{0.441} \right) \right)^{5.08} \quad (B1)$$

Let the spacing index SP (%) be defined as:

$$SP = \frac{\text{Spacing}}{H_{dom}} \approx \frac{10746}{H_{dom} \sqrt{N}} \quad (B2)$$

The stand basal area BA ($m^2 ha^{-1}$) was fitted on the French National Inventory data (558 plots) as:

$$BA = 78.3(SP - 6.96)^{-0.865} (AGE - 5)^{0.521} N^{-0.0937} \quad (B3)$$

Equation (B3) explained 71.3% of the variance and RMSE was

4.19.

The 3 parameter Weibull distribution was fitted on a subset of the same dataset (containing enough diameter classes):

$$\text{The position parameter was } a = 3.18 + 0.253 D_g \quad (B4)$$

$$\text{The scale parameter was } b = -1.53 + 0.697 D_g \quad (B5)$$

$$\text{The shape parameter was } c = 2.30 / (1 - 1.08 \exp(-0.517b)) \quad (B6)$$

where D_g is the quadratic mean diameter (cm), defined as:

$$D_g = 100 \sqrt{\frac{4BA}{N}} \quad (B7)$$

R^2 for equation (B5) was 0.57.

Appendix C. Example of succession model used to parameterize a LayerSet: Kermes oak garrigue Succession Model.

The succession model deals with two *Layers*: shrub and herbs, that show significantly different characteristics in terms of dy-

namics and *Particle* properties. Non linear mixed-effect regression analysis done with package *nlmeFit* of the Statistical Toolbox of the *MATLAB* software was used to fit the following models over empirical data. Random effects of the mixed models accounted for residual variability corresponding to site fertility.

The mean growth depends on stem AGE and light availability (through *Plant* cover fraction C_{plants}). Five fertility classes were defined to account for residual variability. The determination of the model was $R^2 = 0.938$ (84 stems analyzed in Pimont, 2004).

$$H = (0.248 + \Delta H_0 + 0.0462 C_{plants}) \log(AGE + 0.763) \quad (C1)$$

The five fertility classes corresponded to values of $\Delta H_0 \in \{-0.1; -0.05; 0; 0.05; 0.12\}$.

The model for total load ($kg m^{-2}$) was fitted on a Lindqvist-Korf distribution, with an effect of *Plant* cover and a random effect ΔW on the multiplicative parameter:

$$W^{tot} = (5.89 + \Delta W) \exp \left(-2.90 AGE^{-0.378} - 0.941 C_{plants} \right) \frac{C_{shrub}}{0.8} \quad (C2)$$

The determination coefficient of the model was $R^2 = 0.982$ with $\Delta W \in \{-2.33; -1.33; 0; 0.984; 2.88\}$ corresponding to the 5 fertility

classes.

Thin shrub biomass was evaluated as a fraction of total biomass:

$$W_{\text{Shrub}}^{\text{thin}} = W_{\text{tot}} \frac{0.756}{(2.69 + \text{AGE})^{0.377}} \left(1 + 0.501 \text{AGE}^{0.173} + 0.520 \text{AGE}^{0.300} \right) \quad (\text{C3})$$

The three terms in bracket, respectively representing the fractions of leaves, 0–2 mm and 2–6 mm twigs. The determination coefficients of these three fractions were 0.715, 0.605 and 0.927.

Herb biomass was evaluated from herb cover fraction C_{Herb} :

$$W_{\text{Herb}}(C_{\text{Herb}}) = 0.4 C_{\text{Herb}} \quad (\text{C4})$$

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