

MASIFIRE – Map based simulation of fires in forest-urban interface

Reference and user's guide for version 1.0

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VTT Building and Transport

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Abstract This document provides the technical background and user's guide for MASIFIRE – a software for Map based Simulation of Fires in Forest-Urban Environment. The software can be used for the simulation of fire spread in forests with surface and canopy vegetation, and the spreading of fire from the forest to buildings. The model includes the effects of fuel type, wind, moisture and the shape of the terrain. Model results include the fire spread, total heat release rate, production of toxic species and necessary evacuation area for people. The fire spread algorithm is based on the BEHAVE model.		
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Preface

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Appendix A: Glossary

List of symbols

CBH	canopy base height (m)
CBD	canopy bulk density (kg/m ³)
CFB	crown fraction burned
FMC	foliar moisture concentration (%)
FME	foliar moisture effect
I	fireline intensity (W/m)
I'	critical fireline intensity (W/m)
\dot{m}_X	mass loss rate of species X (kg/s)
\dot{Q}''	reaction intensity, heat release rate per unit area (kW/m ²)
Q_{ig}	heat of pre-ignition (kJ/kg)
$R'_{initiation}$	rate of spread of the surface fire leading to initiation of crown fire
$R_{surface}$	rate of spread of the surface fire (m/min)
R_{active}	rate of spread of the active crown fire (m/min)
R_{final}	final rate of spread (m/min)
T	temperature (K)
T_a	ambient temperature (K)
T_w	wall temperature (K)
U_w	wind speed (m/s)
Δt	simulation time step (min)
Δx	cell size of the map (m)
ε	effective heating number of surface fireline
ϕ_w	wind coefficient
ϕ_s	slope coefficient
ρ_b, ρ_w	bulk density of fuel material, density of wall (kg/m ³)
ξ	propagating flux ratio

1. Introduction

Forest fires may cause a significant risk for the buildings that are close to dense combustible vegetation. This risk becomes especially important if the buildings are used to store explosive materials. The combination of an explosion hazard and combustible forest vegetation may lead to extremely fast fire spread and a catastrophic situation if the explosion storage is close to housing or industry. Mathematical modelling of the fire spread in wildland-urban interface may be used to identify the potential of such a catastrophe and to study the possible ways to reduce the risk.

The development and properties of various wildland fire models were recently presented in the review article of Pastor *et al.* [2003]. According to their article, the most widespread modelling systems for wildland fires is BEHAVE [Andrews 1986] which is based on the Rothermel's [1972] model for the spreading rate and fire line intensity in the surface fuels and the classification system of the vegetation fuel [Anderson 1982]. The model includes the effects of fuel load and type, wind, slope and moisture by the use of experimental correlations supporting the relatively simple physical models. Rothermel's model has been used in other computer models too, like FARSITE [Finney 1998].

One of the problems of semi empirical fireline progress models like BEHAVE is their incapability to handle the three-dimensionality and inhomogeneous structure of the vegetation fuel. To avoid such problems Morvan & Dupuy [2004] have developed and validated a computational fluid dynamics model (CFD) for the simulation of fire spread in Mediterranean shrub. The model includes a detailed description of the physical processes including hydrodynamics, radiation and pyrolysis in the vegetation. Due to the complexity of the model, the presented applications have only included two-dimensional cases. Despite this restriction, the model can be used to produce important relations of the fire behaviour and environmental conditions.

For the modelling of the fire spreading from forest to buildings and structures, the traditional models have only been of limited use. A few models have been proposed for the handling of the wildland-urban interface (WUI) fires. Cohen & Butler [1998] studied the ignition of wood materials from the radiation of the forest fire, but included no fire spread model for the vegetation. Rehm *et al.* [2002, 2003] used CFD to predict the three-dimensional flow field around the buildings and were able to model the vegetation fire spread using multi-phase formulation. Despite the rapid development of the computer resources, this models is still difficult and slow to use for a comprehensive analysis of real targets, including relatively large forest area, realistic altitude terrain and buildings. In case explosives storage areas, some kind of mechanism is needed to ignite the neighbouring vegetation in case of explosion.

In this work, a software tool has been developed which combines the BEHAVE model with numerical models to predict ignition of buildings, and spreading of fire through the explosions. The crown fires are simulated using the model of Scott & Reinhardt [2001]. The software is called Map based Simulation of Fires in Forest-Urban Environment (MASIFIRE), and includes the effects of fuel type, wind, moisture and the shape of the terrain. Model results include the fire spread, total heat release rate, production of toxic species and necessary evacuation area for people. The model user interface allows the use of digitized maps to describe the fuel types and terrain.

2. Model description

2.1 Surface fire spread

The model for the spreading of surface fire in the forest bed is based on the BEHAVE model [Andrews 1986]. In BEHAVE the physical and empirical models for surface fire spread, originally presented by Rothermel [1972], were combined with 13 standardized ground fuel types, described by Anderson [1982]. Rothermel proposed that the spread rate of the surface fire is

$$R_{surface} = \frac{\dot{Q}'' \xi (1 + \phi_w + \phi_s)}{\rho_b \varepsilon Q_{ig}} \quad (1)$$

where \dot{Q}'' is the reaction intensity (kW/m^2), ξ is the propagating flux ratio, ϕ_w and ϕ_s are the wind and slope coefficients, ρ_b is the oven dry bulk density (kg/m^3), ε is the effective heating number and Q_{ig} is the heat of pre-ignition (kJ/kg) (heat that is required to bring a unit mass of fuel to ignition temperature). See the original article [Rothermel 1972] for details.

The models were incorporated into MASIFIRE program using fireLib library [Bevins 1996] which provides the models of BEHAVE as an ANSI-C programming library. The fireLib version 1.01 was used, with the following modifications: Two combustion variables, Fuel_ResidenceTimeMax and Fuel_HpuaTot were added, which contain the fire residence time corresponding to smallest surface-area-to-volume-ratio and total amount of heat per unit area, respectively.

2.2 Crown fire spread

The initiation and spreading of crown fires are described by the model of Scott & Reinhardt [2001] which combined the BEHAVE surface fire model with the simple correlations for the crown fire spread. The model calculates the spread rate of active crown fire (see explanations in Appendix A) using the equation

$$R_{active} = 3.34 \cdot \frac{FME}{FME_0} \cdot (R_{10})_{40\%} \quad (2)$$

where $(R_{10})_{40\%}$ is the surface fire spread rate given by the standard surface fuel number 10 at 40 % of the current free wind speed and current slope. FME is the foliar moisture effect which takes into account the effect of foliar moisture content (FMC). FME_0 refers to 100% foliar moisture content. The initiation of crown fires is triggered by the

Byram's fireline intensity of the surface fire I . When the intensity I reaches a critical value I' , the crown fires are possible. I' is calculated from the canopy base height CBH and FMC with the following formula

$$I' = \left[\frac{CBH(460 + 25.9FMC)}{100} \right]^{3/2} \quad (3)$$

The distinction of active and passive crown fires is made based on the value of R_{active} . A crown fire becomes active when R_{active} reaches a critical value $R'_{active} = 3.0 / CBD$ where CBD is the canopy bulk density.

The final spread rate is calculated as

$$R_{final} = R_{surface} + CFB(R_{active} - R_{surface}) \quad (4)$$

where CFB is the crown fraction burned by the fire. Following the example of Scott & Reinhardt [2001], we calculate CFB as a linear function of surface fire spread rate

$$CFB = \frac{R_{surface} - R'_{initiation}}{R'_{SA} - R'_{initiation}} \quad (5)$$

where $R'_{initiation}$ is the surface spread rate leading to initiation of crown fire and R'_{SA} is the surface spread rate at limit $R_{active} = R'_{active}$. By definition, $R'_{initiation} = 60 I' / HPA$, where HPA is the heat per unit area available for combustion. Note that the unit of spread rate is m/min, while the Byram's fireline intensity has units W/m.

2.3 Spreading algorithm

The spreading of the fire is calculated by dividing the simulation area to square cells. The cells correspond to the pixels of the map image. At each time step, the code loops through all the cells that are already burning and calculates the ignition times of the neighbouring cells, based on the rate of spread to that particular direction. Separate spread rates are used for the surface and crown fires.

The fire spread neighbourhood may contain only eight closest neighbours or a larger area, up to radius given by the user. When larger fire spread neighbourhood is used, the spread pattern becomes smoother. On the other hand, large neighbourhood may cause unexpected behaviour in some cases like narrow fire barriers (e.g. water streams).

The simulation proceeds with a time step Δt which is automatically adjusted to limit the distance of fire spread within the time step to 0.2 times the cell size Δx , i.e.

$$\Delta t \leq \frac{0.2\Delta x}{R_{\max}} \quad (6)$$

where R_{\max} is the maximum rate of spread. The initial value for Δt is one minute. An additional limiter is introduced to prevent time step from getting smaller than five seconds.

2.4 Transport of toxic products

Both the forest and building fires produce species that may be harmful for people. A capability to calculate the transport of toxic species by the wind is therefore implemented in MASIFIRE. Memarzadeh [1995] presented a model for Gaussian dispersion downwind from a point source. According to Memarzadeh's model, the ground level concentration of species X at downwind distance x and normal distance y is

$$\chi_X(x, y) = \frac{\dot{m}_X}{\pi U_w \sigma_y \sigma_z} \cdot \exp\left[-0.5\left(\frac{y}{\sigma_y}\right)^2\right] \cdot \exp\left[-0.5\left(\frac{h(x)}{\sigma_z}\right)^2\right] \quad (7)$$

where \dot{m}_X is the mass loss rate of the species (kg/s), U_w is the wind speed (m/s) and σ_y and σ_z are the plume dispersion parameters in lateral and vertical directions, respectively. The plume rise $h(x)$ is calculated using Nettetville's [1990] solution of the buoyant plume equations in windy environment. Currently, a neutral atmosphere is assumed, which leads to the following solution of the plume rise

$$h(x) = \left\{ \frac{3}{\beta^2 f^2 U_w} \left[F_0 + fM_0 - \{fM_0 + F_0(\tau + 1)\} e^{-fx/U_w} \right] + \left(\frac{R_0}{\beta} \right)^3 \right\}^{1/3} - \frac{R_0}{\beta} \quad (8)$$

where f is the atmospheric turbulent buffet frequency, β is the entrainment coefficient, F_0 , M_0 and R_0 are the initial values of plume buoyancy, momentum and radius after the plume has bent over. In the current implementation of the model the following assumptions have been made:

$$\frac{dT_a}{dz} = -\frac{g}{C_p} \text{ (neutral environm.)}$$

$$T_a = 293.15 \text{ K}$$

$$\Delta T = 70 \text{ K}$$

$$\beta = 0.6$$

$$i_E = 0.25$$

$$\Lambda_E = 250 \text{ m}$$

$$f = 2\beta i_E U_w / \Lambda_E$$

$$P = 1013 \text{ mbar}$$

where, T_a is the ambient temperature, ΔT is the temperature rise in the smoke, i_E is the dimensionless intensity of Eulerian atmospheric turbulence, Λ_E is the length scale of the atmospheric eddies and P is the background pressure.

The above equations are used to calculate the ground level concentrations of the toxic products in the downwind direction, based on the total heat release rate, mass release rate of each species, fire diameter and wind speed. The critical distance in the downwind and perpendicular to that are found based on the 8h and 15 min concentration limits given by the user. When the program starts, CO₂, CO and PM₁₀ particles are included as species. PM₁₀ particles are the fine particles smaller than 10 μm . The default emission factors (mass of released species per mass of burned fuel) and concentration limits of these species are given in Table 1. The user should always use values that are proper for the particular case, and add more species if necessary.

MASIFIRE calculates the evacuation areas based on the ground level concentrations and both 8h and 15 concentration limits. These areas are not based on the 8h or 15 min averages but calculated using instantaneous values of the concentrations. They don't take into account the transport time delays either.

Table 1. The default species, their emission factors and concentration limits.

	Emission factors (kg/kg)		Concentration limits (kg/m ³)	
	Forest [1]	Buildings	8h	15 min
CO ₂	1.521	1.6 [2]	9.1×10^{-3} [4]	-
CO	0.14	0.06 [2]	35.0×10^{-6} [4]	87.0×10^{-6} [4]
Particles PM ₁₀	0.014	0.015 [3]	150×10^{-9} [5]	-

[1] From Battye & Battye [2002].

[2] From Persson & Simonson [1998].

[3] From Table 3-4.14 of Tewarson [2002]

[4] From HTP-arvot 2002.

[5] From Sandberg *et al.* [2002].

2.5 Ignition of buildings from forest fire

As the surface or forest fire approaches a building, it heats up the walls of the building due to the radiation and convection. As the walls heat up, they may ignite or simply break down, exposing the contents of the building to the fire. In MASIFIRE, the surface or forest fire spreads from cell to cell. These cells are also used when the heat transfer from fire to building walls is calculated. For the calculation of the radiative heat flux, each map cell is associated with a radiating point source above the centre of the cell, as shown in Figure 1. The radiative power is set to 30 % of the local heat release rate. For each cell and each wall of the building (N, E, S and W), a configuration factor is calculated based on the angle between the wall normal and the line of sight. It is assumed that the point sources are on the same height as the wall midpoint. The total incoming radiative flux is a sum of the cells with non-zero configuration factors. In practice, the summation is limited inside some radius, outside which the radiation contributions are assumed to have no practical importance. At the moment, this radius is 50 m.

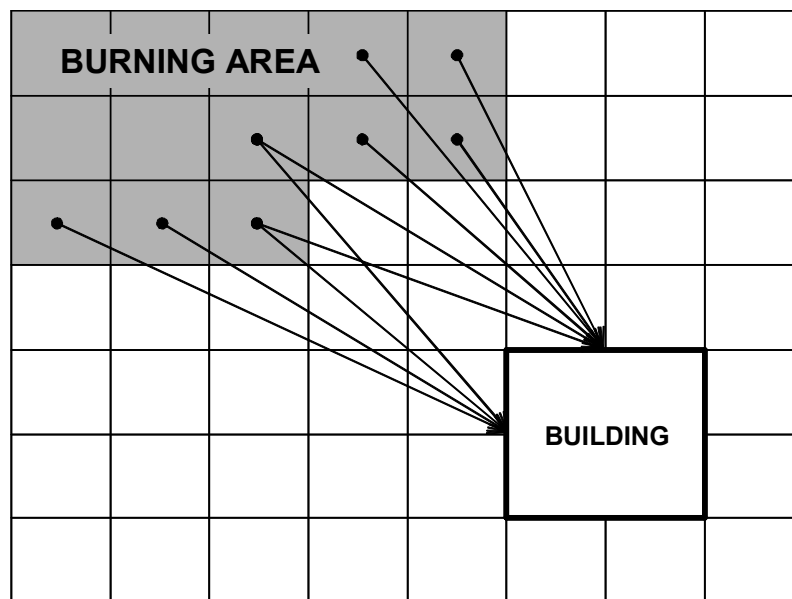


Figure 1. Calculation of radiative heat flux from forest fire to building walls.

For the computation of the convective heat transfer one needs to know both the temperature and the velocity of the gas close to the surface. Unfortunately, there is no good model available that would give these quantities for a point downwind from a burning area of arbitrary shape. Therefore, a series of CFD simulations was carried out using the NIST Fire Dynamics Simulator software [McGrattan et al. 2002] where the properties of leaning fire plume flowing over a building was studied in a two-dimensional geometry. An example of the flow is shown in Figure 2 showing the temperature field of a leaning fire plume. The building is on the left and the distance

from the building wall to the 5 m wide fire is 15 m. The wall height is 4 m. In the simulations, the wall to fire distance L was varied from 5 to 20 m, heat release rate of the fire \dot{Q}'' was varied from 50 to 1000 kW/m² and windspeed U_w from 0 to 15 m/s. At each combination, the maximum gas temperature in the vicinity of the wall and the corresponding flow velocity were used for the calculation of the convective heat flux. A first order (linear) polynomial was then fitted to the data using the least-squares technique. As a result, we got the following formula that gives the convective heat flux to a wall at ambient temperature (20 °C)

$$\dot{q}_c''(U_w, L, \dot{Q}'') = 282.9 + 0.8948\dot{Q}'' - 52.27L + 166.1U_w \quad (\text{W}) \quad (9)$$

This formula is valid for the ranges mentioned above. During the application to the wall, the convection flux must be corrected for the increased wall temperature. This is done by decreasing the convective heat transfer by $h(T_{wall} - T_0)$, assuming $h = 5 \text{ W/mK}$.

NIST

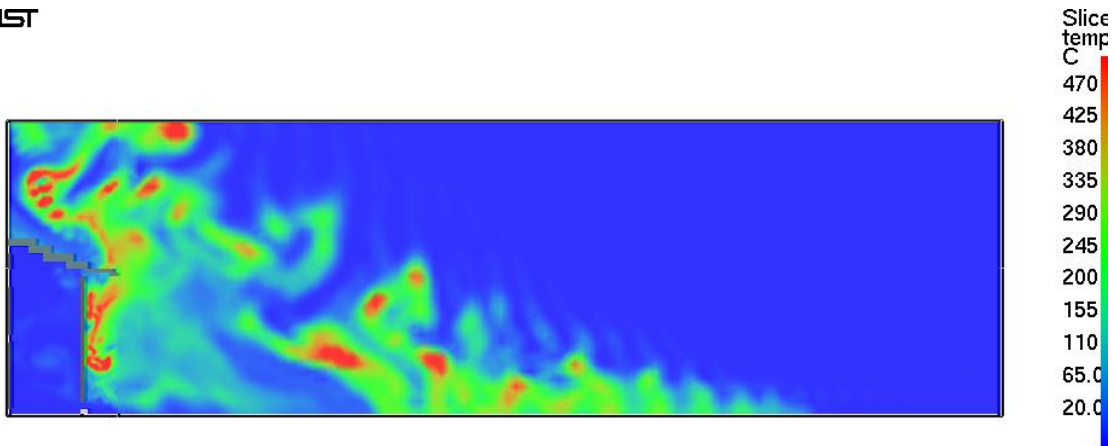


Figure 2. An example of the FDS simulation of the interaction of a building (on the left) and a wind driven fire plume with windspeed of 5 m/s, heat release rate of 1 MW/m² and fire to wall distance of 15 m.

We assume that all the cells that are located within a 90 degrees wide sector upwind from the building may contribute to the convective heat transfer. This 'upwind' area is found by going to each cell inside the ignition neighbourhood (see Appendix A), and calculating the angle between the wind direction and line from cell centre to building centre. If the angle is less or equal to 45 degrees, the cell belongs to the 'upwind' area. This technique is illustrated in Figure 3. The above correlation is then applied to each cell inside the 'upwind' area, and the highest heat flux is chosen to for the heat transfer calculation of all four walls of the building. This is somewhat inaccurate but conservative approximation. To summarize, the radiative heat flux of the building wall depends on the direction of the wall (north, east, south or west) but the gross convective heat flux is the same for each wall.

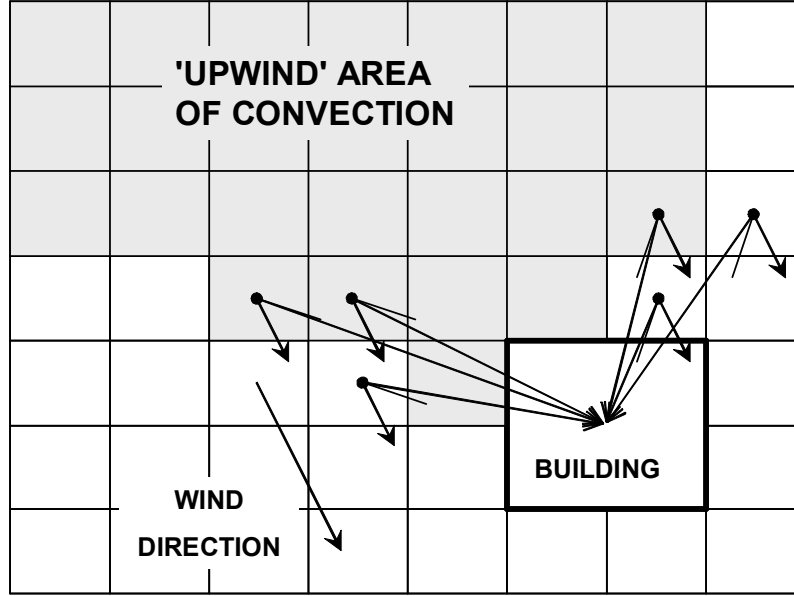


Figure 3. Defining the upwind area of convective heat transfer from forest fire to building walls.

For the calculation of the wall heat transfer, the walls are assumed to be thermally thick, and one-dimensional heat conduction equation for the material temperature is applied in the direction x pointing into the solid (the point $x = 0$ represents the surface)

$$\rho_w c_w \frac{\partial T_w}{\partial t} = \frac{\partial}{\partial x} \left(k_w \frac{\partial T_w}{\partial x} \right) ; \quad -k_w \frac{\partial T_w}{\partial x} (0, t) = \dot{q}_c'' + \dot{q}_r'' \quad (10)$$

where ρ_w , c_w and k_w are the constant density, specific heat and conductivity of the material; \dot{q}_c'' is the convective heat flux and \dot{q}_r'' is the net radiative heat flux to the surface. Similar boundary condition is applied to the back surface, assuming convection and radiation to a space at ambient temperature. The above equation is solved using a finite difference method with uniform grid in the x -direction and the same time step that is used for the forest fire spread. An implicit Crank-Nicholson scheme is used for the time integration. The temperature field of the wall is solved only to the point when the surface reaches the ignition or breaking temperature given by the user.

2.6 Ignition of surface fires from explosion

During the explosions hot and burning fragments are ejected to the surroundings. These fragments may ignite the forest fuels and cause a rapid spreading of the forest fire to a large area. The formation mechanism of the fragments is an extremely complicated process that depends on the mass and properties of the explosive material and its container. In MASIFIRE, we do not attempt to predict the explosion behaviour of the

explosive objects, but let the user define all the necessary information. Starckenberg *et al.* [2001] have studied the propagation probabilities of ammunition stacks, being able to produce probability vs. distance curves for various propagation mechanisms, i.e. detonation, burning, mechanical damage or mechanical hit. Here we assume that the probability of ignition of the dead surface fuels behaves analogously and define a probability curve using two distances R_1 and R_2 : The probability of ignition is measured as number of ignitions per area. At distances shorter than or equal to R_1 , the number of ignitions is $1/\text{m}^2$. At R_2 the number of ignitions is $0.1/\text{m}^2$ and zero outside the radius of R_2 . Between these two values the ignition density varies proportional to $1/r^2$. The definition of the ignition density curve is illustrated in Figure 4. The parameters R_1 and R_2 are always associated with the storage building and are not affected by the contents of the building.

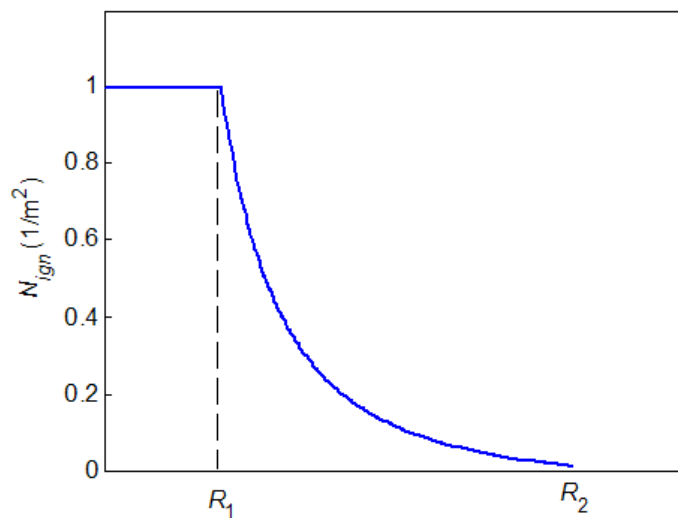


Figure 4. Definition of the surface fire ignition curve.

3. System requirements and installing MASIFIRE

3.1 Hardware and software requirements

Both the speed of the computation and the memory requirement are strongly dependent on the size of the map used in the simulation. For speed, the rule is simple: Faster CPU is always better. A rough estimate of the memory requirement set by MASIFIRE is

$$\text{Memory requirement} = 22 * N * 8 / 1E6 \text{ [MBytes]}$$

where N is the number of pixels in the map. In addition to this, Matlab itself typically requires tens of megabytes of memory. For a map with 1000×500 pixels, the MASIFIRE's memory requirement would therefore be approximately 88 MB. Similarly, for a map with 2000×2000 cells, it would be 704 MB! It is easy to see, that the use of maps with too high resolution or too wide area should be avoided. For graphics, a monitor with a minimum of 1152 by 864 resolution and 16 bit colours is needed. A 1280 by 1024 resolution is recommended.

MASIFIRE is a Matlab GUI-application (GUI = graphical user interface) with additional simulation routines (MEX-libraries) programmed with C-language. To run MASIFIRE either of the following environments is needed:

- Matlab 7.0 (R14) or higher.
- Matlab Component Runtime (MCR) of release R14 or higher installed on the computer. (This option is not valid until a precompiled version of MASIFIRE becomes available.)

Binary versions (.dll) of the MASIFIRE MEX-libraries are available for Microsoft Windows operating system. For other operating systems (e.g. Linux), users have to compile the mex files by themselves. The following steps are required to compile:

```
mex runmasi.c fireLibmex.c
mex firelibgetfuel.c fireLibmex.c
mex mapimg.c
mex mapfix.c
```

3.2 Installing MASIFIRE

MASIFIRE is distributed as a Matlab GUI package that needs many files to work. Below is a list files needed in MASIFIRE 1.0. Copy these files to an installation directory, and add that directory to Matlab path.

M-files:

BuildingSetup.m	arrow.m	mfsettings.m
FuelCatalogManager.m	showwindow.m	GetNumberDialog.m
FuelSetup.m	findtoxicarea.m	masifire.m
windplume.m		

Fig-files:

BuildingSetup.fig	FuelSetup.fig
masifire.fig	FuelCatalogManager.fig
GetNumberDialog.fig	mfsettings.fig

MEX-files (dll-files on Windows systems)

fireLibGetFuel.dll	mapping.dll
mapfix.dll	runmasi.dll

Alternatively, MASIFIRE can be distributed as an executable masifire.exe, compiled with Matlab Compiler. To run masifire.exe, install first Matlab Component Runtime (MCR) by running the MCRInstaller.exe.

IMPORTANT: Make sure that the directory path of Matlab Component Runtime does not contain spaces. In general, any Matlab components should not be installed under C:\Program files -directory. Spaces in directory names may cause errors in some Matlab functions.

4. User interface

4.1 Main window

When you start MASIFIRE, either by typing 'masifire' to a MATLAB prompt, or by running the masifire.exe (MCR version), the main window opens on your screen. By default, the window is maximized to full your screen, but you can make it smaller as usual.

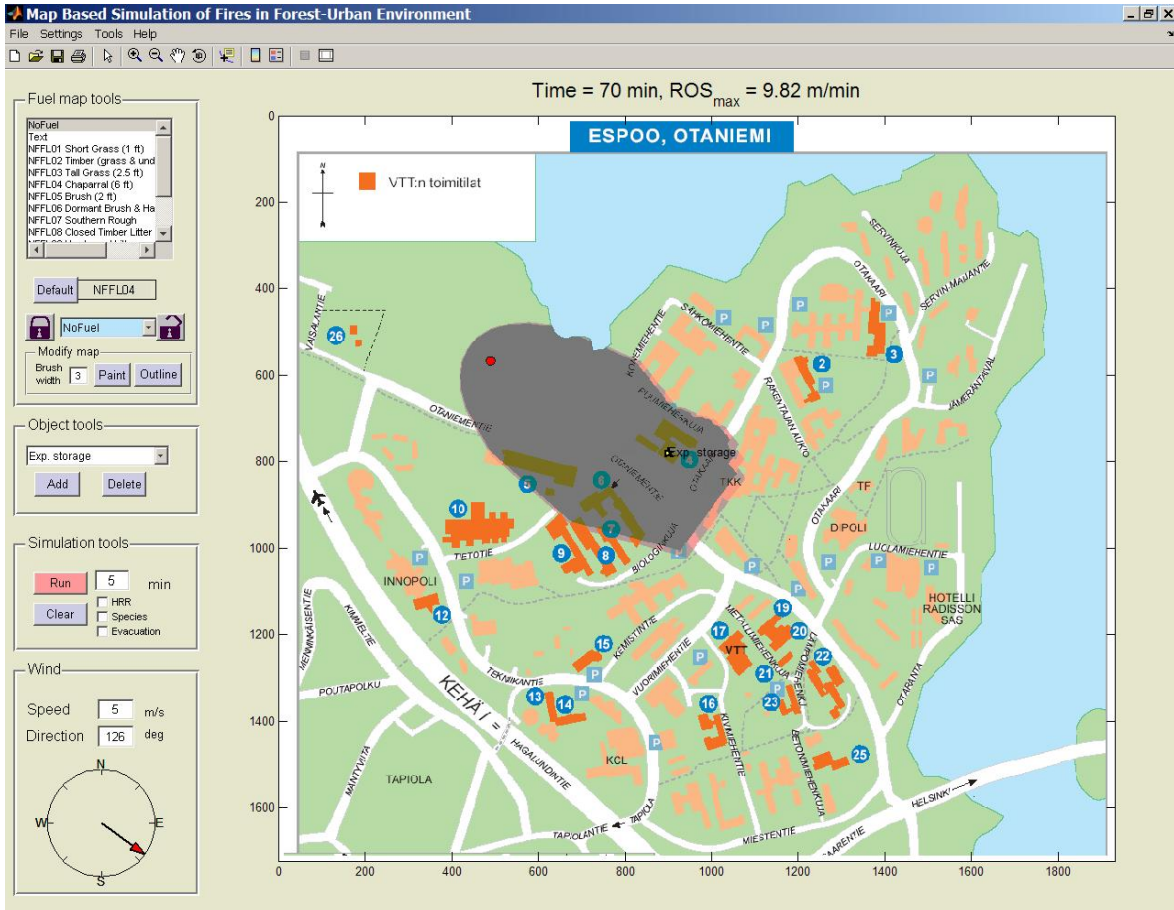


Figure 5. MASIFIRE main window.

The main window contains the following areas:

4.1.1 Map axis

The map axis is used to visualize the map image and to show the proceeding of the fire fronts and burning area. The burning and burn-out areas are shown by changing the colour of the map. The colours depend on the original colour of the map. The colours for white background colour are shown in Figure 6. You can zoom the map with mouse by selecting the zoom-tool from the toolbar, or by pressing z-key.

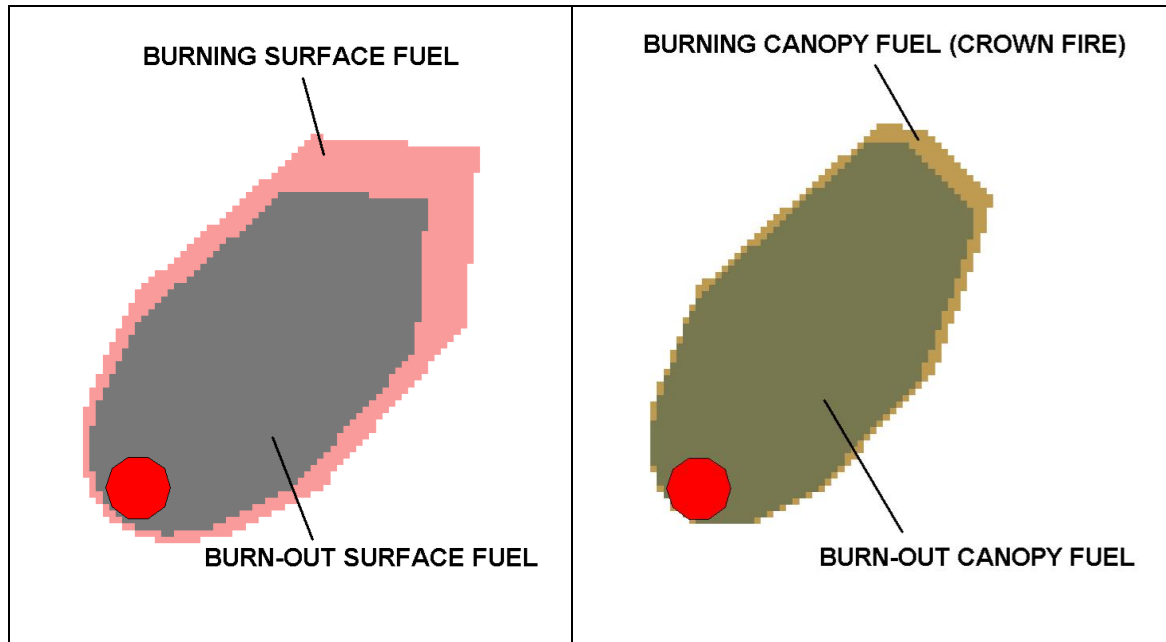




Figure 6. The colours of the burning and burn-out surface fuel (left image) and canopy fuel (right image) on a white background.

4.1.2 Fuel map tools

On the 'Fuel map tools' panel you can choose any of the available fuel models from the scrollable list box, and either make it a default fuel, or bind that fuel to some of the map colours. To bind or unbind a fuel model, click on the button with lock  or open lock , respectively.

New colours can be added to the map by *painting* and *outlining*. In both operations, mouse is used to define the area. In painting, the mouse pointer is used moved by left mouse button down to add the colour. In outlining, the borders of the coloured area should be given. After the painting, the colour should be bound with some of the fuel models, but outlining always uses the fuel currently selected.

4.1.3 Object tools

The second panel on the left hand side is the 'Object tools' panel. There you can choose some of the object types, add the objects on the map or delete existing objects. The object types are

- Ignition point. Add ignition points by clicking the left mouse button over the map. Stop adding by clicking the right mouse button. The ignition points appear

on the map as red circles. When you add an ignition point, the ignition time of the corresponding cell of the fuel map is set to the current time. Delete ignition points one by one by selecting Ignition points from the menu, pressing 'Delete' button and clicking the mouse over the point.

- Ignition area. A larger area of the map can be set on fire in the beginning by adding an ignition area. Add the corners of the area (as many as you wish) by clicking the left mouse button. Right mouse button adds the last corner. Be sure not to bring any other program window on the top of the MASIFIRE window when adding ignition area. Delete an existing ignition area by selecting Ignition area from the menu, pressing 'Delete' button and clicking the mouse over the area.
- Altitude contours. For the definition of the terrain you can add altitude contours by clicking the points of the contour with left mouse button. Right button adds the last point, after which you are asked to click the mouse inside the contour if you are defining a hill, or outside if you are defining a pit. All the contours must be closed and non-overlapping. If the contour continues outside the map you should add at least two points outside the visible map area, as shown in Figure 7. The accurate locations of the points outside the map are usually not very important. When you have added all the contours, you should generate the terrain (Tools-menu) and visually check it (Tools-menu /Show terrain). The map should have the correct scaling before the adding of the contours because the contours are not updated by any scaling operations. Delete an altitude contour by selecting Altitude contour from the menu, pressing 'Delete' button and clicking the mouse inside the contour.
- Adding and deleting buildings. In the end of the object Pop-up menu are listed the available building types. Add a building by pressing 'Add' button and clicking your left mouse button over the map. Delete a building by pressing 'Delete' and clicking over an existing building. The available building types are defined in the 'Building definitions' -tool (Settings menu).

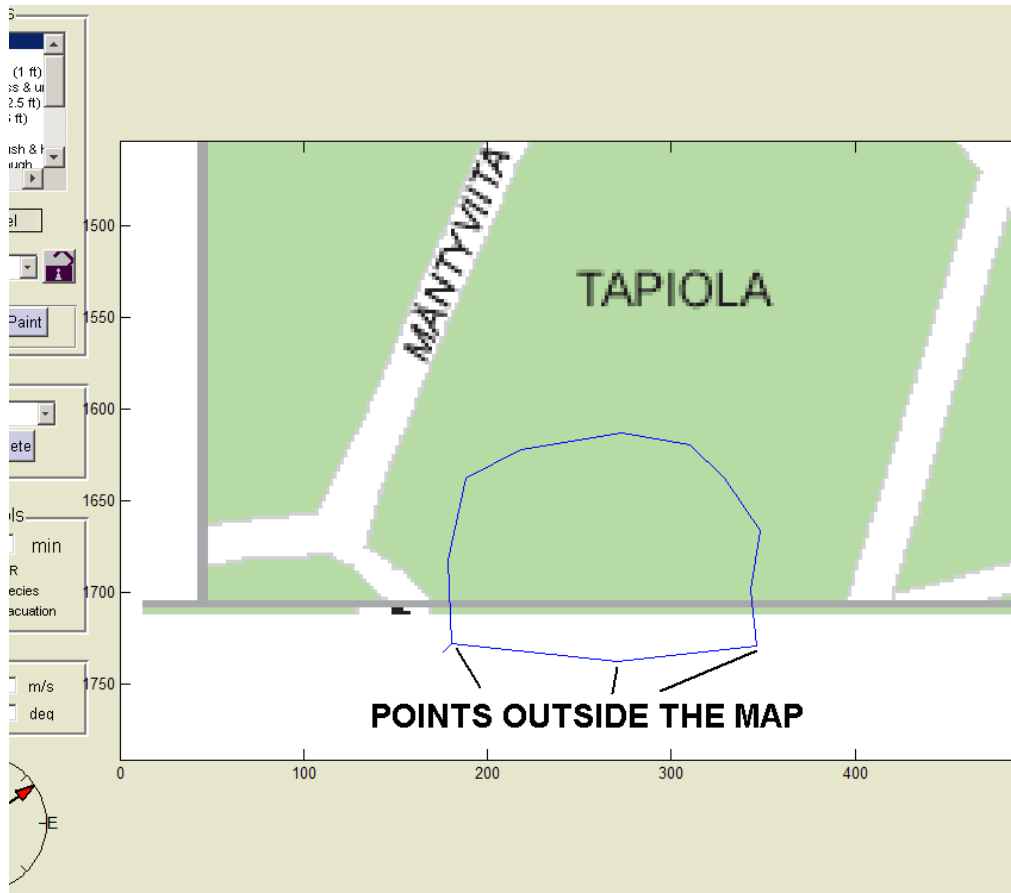


Figure 7. Adding an altitude contour on the edge of the map.

4.1.4 Simulation tools

The third panel on the left hand side of the MASIFIRE main window is used for running the simulations. Give the simulation time by typing it into the text box in minutes, and run the simulation for the given amount of time by pressing the 'Run' button. MASIFIRE will

Pressing 'Clear' will clear the results and set the time to zero. Select additional results by selecting one of the following:

- HRR. When selected, MASIFIRE plots the total heat release rate in a separate window in the end of the simulation period.
- Species. When selected, MASIFIRE plots the production rates of the current list of species in a separate window in the end of the simulation period.

- Evacuation. When selected, MASIFIRE plots the evacuation areas on the map, and plots the maximum evacuation distance for each species in a separate window. The evacuation areas are shown with colourful lines. One line corresponds to one species and one concentration limit (8h or 15 min exposure). The legend on the right hand side of the main window explains the colours. If the legend goes under the map, deselect the 'Evacuation' and select again.

4.1.5 Wind

The last panel on the left hand side of the MASIFIRE main window is used for the definition of wind speed (m/s) and direction. The wind speed should correspond to the speed in the open flat terrain, at height of 6.1 m. The direction is defined as degrees from north in clock-wise direction. Set the direction either by typing in the degrees as a number or by dragging the red arrow with left mouse button. The left arrow becomes visible when the map is read in.

4.2 Fuel setup window

The calculation of fire spread in forest and surface fuels is based on the definition of fuel models and their association to the different areas of the map. Every type of vegetation that appears on the map should have an own fuel model. MASIFIRE stores the fuel models in fuel catalogs, which makes it easier to organize, save and load the fuel models. The fuel catalogs and fuel models are defined on a Fuel setup window, which starts from the Settings menu of the main window. Fuel setup window is shown in Figure 8.

4.2.1 Fuel catalog

In the 'Fuel catalog' panel you can create new catalogs, save the selected catalog on the hard disk, load a previously saved catalog and close the selected catalog. Pressing 'Fuel catalog manager' button opens a separate dialog, where you can copy individual fuel models from a catalog to another. This is very useful when you create new fuel models by modifying existing models, and want to collect the new fuel models to a separate catalog.

When MASIFIRE is started, the fuel catalog is initialized with 13 standard fuel models [Anderson 1982].

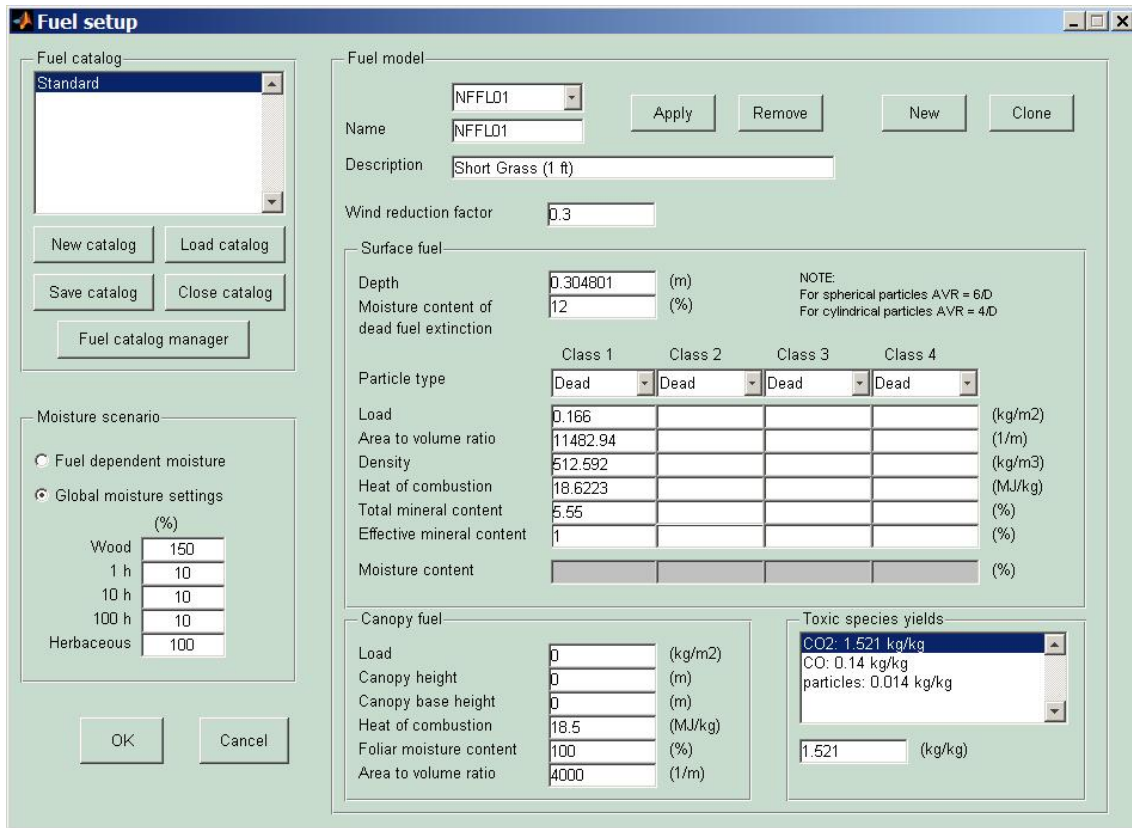


Figure 8. Fuel setup window.

4.2.2 Fuel model

The individual fuel models of the currently selected fuel catalog are defined in the 'Fuel model' panel. In the top of the panel is a Pop-up menu which is used to select the fuel model. If the fuel model is modified, the changes should be saved by pressing the 'Apply' buttons. Buttons are also available for removing the fuel model from the catalog, creating a new model, or copying the current fuel to the end of the catalog (Clone).

Fuel model's Name and Description are text strings, used to identify the model.

Wind reduction factor is used to calculate the actual wind speed at the ground fire flame height (typically 1 to 2 m), by multiplying the open terrain wind speed given in the main window. The default value is 0.3 but even values 0.1 may be used for dense fuels.

4.2.3 Surface fuel

In 'Surface fuel' panel you should give the following properties for the surface fuel:

- Depth (m) is the height of the fuel layer from the ground.
- Moisture content of dead fuel extinction (%) is the critical moisture of dead fuels, above which they are not assumed to burn.

The natural fuels are not homogenous material but a wide distribution of different grasses, shrubs, litter and live vegetation. To describe this kind of mixture of fuels with a relatively small number of properties, strong simplifications must be made. To describe the range of the different contents, each surface fuel may consist of up to four (minimum one) classes of fuel types, called particles. Each particle class has the following properties:

- Particle type is either dead, live herbaceous, or live woody stem.
- Load is the mass of particles per unit area (kg/m^2).
- The particle size is defined as surface area to volume ratio (AVR), which can be calculated for spherical particles as $\text{AVR} = 6/d$ and for cylindrical particles as $4/d$. Here d is the particle diameter. AVR has units $1/\text{m}$.
- Density is the oven-dry density of the material (kg/m^3).
- Heat of combustion is the energy that is released when one unit mass of particle mass burns (MJ/kg).
- Total mineral content (%), effective mineral content (%). See Rothermel [1972] for details.
- Moisture content. Each particle type may be given own moisture content. These values are used only if 'Fuel dependent moisture' is checked on the 'Moisture scenario' panel of the Fuel setup window. (This feature is not implemented in MASIFIRE 1.0).

4.2.4 Canopy fuel

In order to predict the initiation and spreading of crown fires, the properties of the canopy should be defined for all fuel models. The 13 standard fuel models do not have canopy at all. The definition of canopy fuel is simpler than the surface fuels, as there is only one class of fuel particles. 'Canopy fuel' panel has the following fields:

- Load is the available canopy fuel per unit area (kg/m^2). This can be estimated using the information on the canopy biomass of trees and the number of trees per square meter.
- Canopy height is approximately the height of the trees from the ground (m).
- Canopy base height is the lowest height above the ground at which there is a sufficient amount of canopy fuel to propagate fire vertically into the canopy.
- Heat of combustion is the energy that is released when one unit mass of canopy mass burns (MJ/kg).
- Foliar moisture content is the moisture content of the fuel particles (%).
- Area to volume ratio ($1/\text{m}$) is the measure of typical particle size. See the explanation of the surface fuel properties.

4.2.5 Toxic species yields

This panel is used to define what is the yield of each toxic species for the current fuel model. The yield is defined as a released mass per one kg of burned fuel. To modify the yield values, choose the species from the list, type in the new value into the text box below, and press enter.

4.2.6 Moisture scenario

The moisture of the fuel may be either fuel specific or global. Global settings are handy when you want to study the effect of the weather or daytime on the whole simulation area. (The fuel dependent moisture scenario is not implemented in MASIFIRE 1.0). Five different moisture content values are used:

- Wood means the moisture of the live woody fuels. The default is 150 %. Woody fuels are perennial and usually have surface-area-to-volume ratios from 3300 to 6600 1/m.
- 1h, 10 h and 100 h mean the moisture contents of size categories of dead fuels corresponding to one-hour, ten-hour and hundred-hour drying times. The one-hour (1-h) timelag dead fuel category includes fuels from 0 to 0.64 cm in diameter, the ten-hour (10-h) timelag dead fuel category includes fuels from 0.64 to 2.54 cm in diameter, and the hundred-hour (100-h) timelag fuel category includes fuels from 2.54 to 7.62 cm in diameter. Larger fuels are not considered in the simulation.
- Herbaceous means the moisture of live herbaceous fuels. Live herbaceous fuels usually have surface-area-to-volume ratios from 4900 to 11,500 1/m.

4.3 Building setup window

For the definition of building types, a separate Building Setup window is used. You can enter Building Setup from the Settings menu of the MASIFIRE main window. Building Setup window has three sections; the actual building types are defined in own panel on the right. Possible contents of the building and wall types are also defined in own panels. The basic rule is that before the ignition, the behaviour of the building is determined by its wall type, as the walls are heated up by the forest fire. After the ignition the contents of the building determine its behaviour.

In the up left corner of the window are buttons for saving and loading of the whole setup on the hard disk. 'Load' button replaces the current settings by the contents of the loaded file. 'Load Increm.' load the contents incrementally, adding the building, content and wall types to the end of the corresponding lists of current types. Building Setup window is shown in Figure 9.

4.3.1 Content Types

After the ignition, the behaviour of the building is determined by its contents. In this panel you can modify or remove the existing content types, create new types or make a clone of the current type. Press 'Apply' to save the modifications to the currently visible content type. Each content type has the following fields:

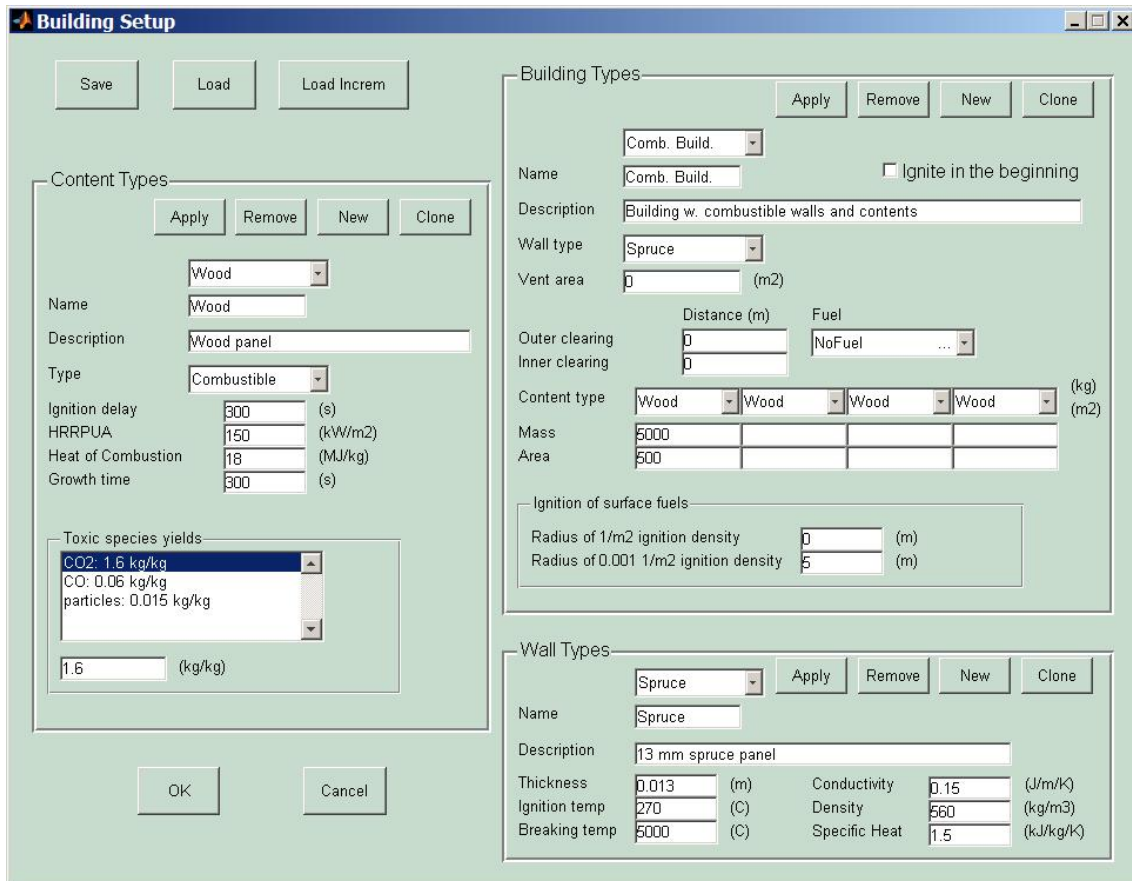


Figure 9. Building Setup window.

- Name and Description are used to identify the content type.
- Type defines the hazard division, and is one of the following
 - Combustible - No explosion can take place
 - Explosive 1.1 - Explosives with a mass explosion hazard
 - Explosive 1.2 - Explosives with a projection hazard
 - Explosive 1.3 - Explosives with predominantly a fire hazard

This information is currently used only to make a distinction between combustible and explosive materials. How the material actually behaves, must be defined by the user.

- Ignition delay (s) is the time that is needed from the ignition or breaking of the building walls to the ignition of the content. However, if some of the explosive contents of the building ignites (explodes), all the other contents are also ignited. Ignition delay and growth time parameters are explained in Figures 10 and 11 for combustible and explosive fuels, respectively.

- HRRPUA, the heat release rate per unit area (kW/m^2), is used to calculate the heat release rate of combustible content.
- Heat of combustion ΔH_c (MJ/kg) is used to predict burning time of combustible content.
- Growth time (s) t_g determines the time constant of the heat release rate development. For combustible fuels it is the growth rate of the t^2 -type heat release rate curve (the time when the heat release rate reaches 1000 kW). In fire safety engineering, the growth times are usually defined based on the following categories:

Growth type	Growth time t_g (s)	Typical material
Slow	600	Floor coverings
Medium	300	Shop counters, office furniture
Fast	150	Bedding, displays and padded work-station partitioning
Ultra fast	75	Lightweight furnishing, upholstered furniture, packing material in rubbish pile, cardboard or plastic boxes in vertical storage arrangement
	< 75	Combustible liquids

For explosives, the growth time is the duration of the explosions. Ignition delay and growth time parameters are explained in Figures 10 and 11 for combustible and explosive fuels, respectively.

- The yields of toxic species from the burning or explosion of the content is defined in a way similar to the fuel model definition, in the previous section.

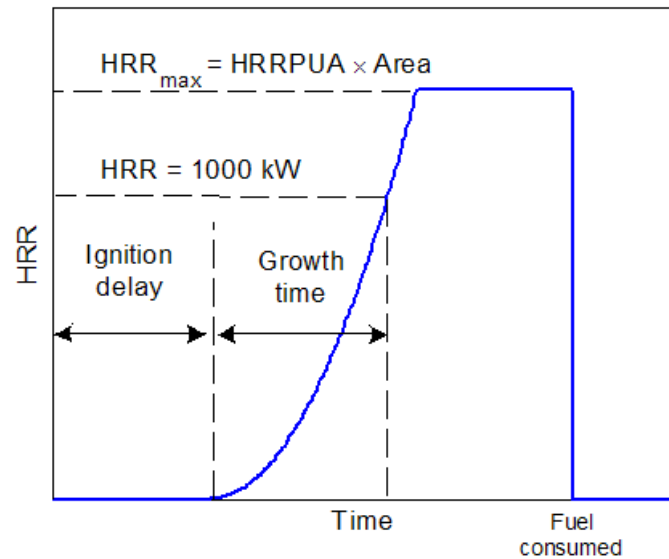


Figure 10. Definition of the heat release rate curve for combustible fuel.

4.3.2 Wall types

Each building has walls of some defined type. This panel allows the modification and removing of existing wall types, definition of new wall types and cloning of the current wall type to the end of the list. Press 'Apply' to save the modifications to the currently visible wall type. Each wall has the following properties:

- Name and Description are used to identify the wall type.
- Thickness, conductivity, density and Specific heat are the physical and thermal properties of the wall. These properties should include the effect of the moisture, as the moisture content of the material is not separately defined.
- Ignition temperature is the critical wall surface temperature where the wall is assumed to ignite. This method can be applied to, for example, wooden walls.
- Breaking temperature is the critical wall surface temperature where the wall is assumed to break down. This method can be applied to wall that are made of, for example, gypsum board.

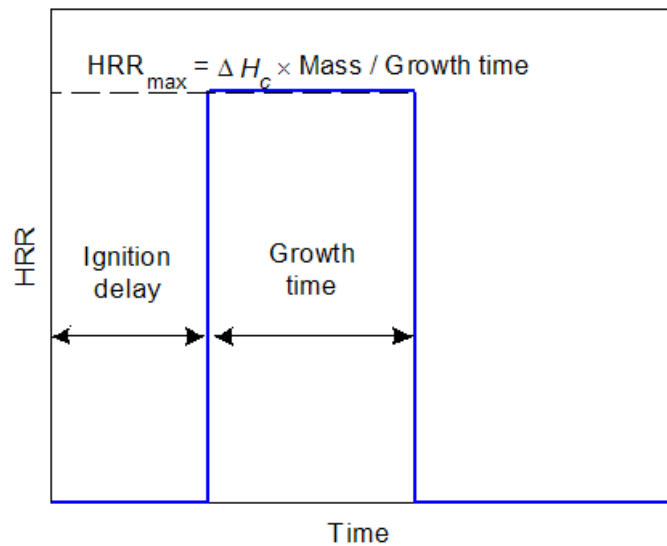


Figure 11. Definition of the heat release rate curve for explosive fuel.

4.3.3 Building Types

This panel allows the modification and removing of existing building types, definition of new types and copying (Clone) of the building type to the end of the list for further modification. Press 'Apply' to save the modifications to the currently visible building type. Each building has the following properties:

- Name and Description are used to identify the building type.
- To start the fire from the building, the checkbox with text 'Ignite in the beginning' should be selected. The contents of the building will then ignite after the ignition delays corresponding to each content type.
- Wall type refers to one of the types defined in the 'Wall Types' panel. Each building is assumed to have four walls (north, east, south and west) of same type.
- Vent area (m²) is area of openings on each wall. (This property is here for future, not used in MASIFIRE 1.0.)
- To reduce the probability of fire spread from a forest fire to a building, the forest fuel is typically cleared from the close neighbourhood of the building. Inside the outer clearing distance there is some fuel, which is defined in the 'Fuel' Pop-up menu. This is typically some surface fuel like grass. Inside the inner clearing distance there is no fuel at all. This is typically from zero to few meters.

- Each building may have up to four types of content. These types of contents are selected from the four pop-up menus, and the mass (kg) and surface area (m²) of the content are given below.
- Both the combustible and explosive content may cause the ignition of the surface fuels surrounding the building. The ignitions take place during the time period set by the shortest ignition delay and heat release rate growth time of the current contents. The probability of ignitions is defined as number of ignitions per square meter of forest. The first radius corresponds to the ignition density of 1/m² and the second for 0.001 ignitions /m². See Figure 4 for more details.

4.4 General parameters

Some general parameters of MASIFIRE can be set using the 'General parameters' window, which is entered from the Settings menu of the main window. A picture of the window is shown in Figure 12. The available parameters are

- Simulation time step (min). This is the initial and maximum value of the simulation time step. During the simulation the time step is adjusted as explained in Section 2.3.
- Map pixel size (m). The scale of the map is determined by the size of the pixels in meters. The scale can be modified either by typing the pixel size directly, or by calibrating the map scale using some known distance on the map. See section 5.2.1.
- Mapfix neighbourhood. This integer number determines the radius of the neighbourhood during the MapFix operation. See Appendix A and Section 4.4.
- Ignition point radius (m) is the size of the red circles showing the location of ignition points on the map. The same length is also used as a size of the buildings.
- Printing interval (min) determines how often the proceeding of the simulation is shown on the map.
- Spread neighbourhood determines the number of cells in each direction for which the ignition time is calculated during the fire spread modelling. Higher number gives smoother spreading patterns, but may lead to unexpected behaviour in some cases like narrow fire barriers (e.g. water streams).

- Height difference between altitude contours (m) is used in the generation of altitude terrain.
- Resolution for the 3D terrain visualization (200) is the number of points in x-direction when the 3D surface of the terrain is generated.
- 'Show map objects in 3D image' should be selected if the objects like buildings and ignition areas should be displayed in the 3D surface of the terrain.
- The list of toxic species is defined here. The buttons on the right let the user introduce new species, remove some of the current species and save the changes. To modify the properties of a species, select it from the menu and type in the emission factors and concentration limits to the corresponding text boxes. Use NaN, if the information is not available. Remember to save the changes.

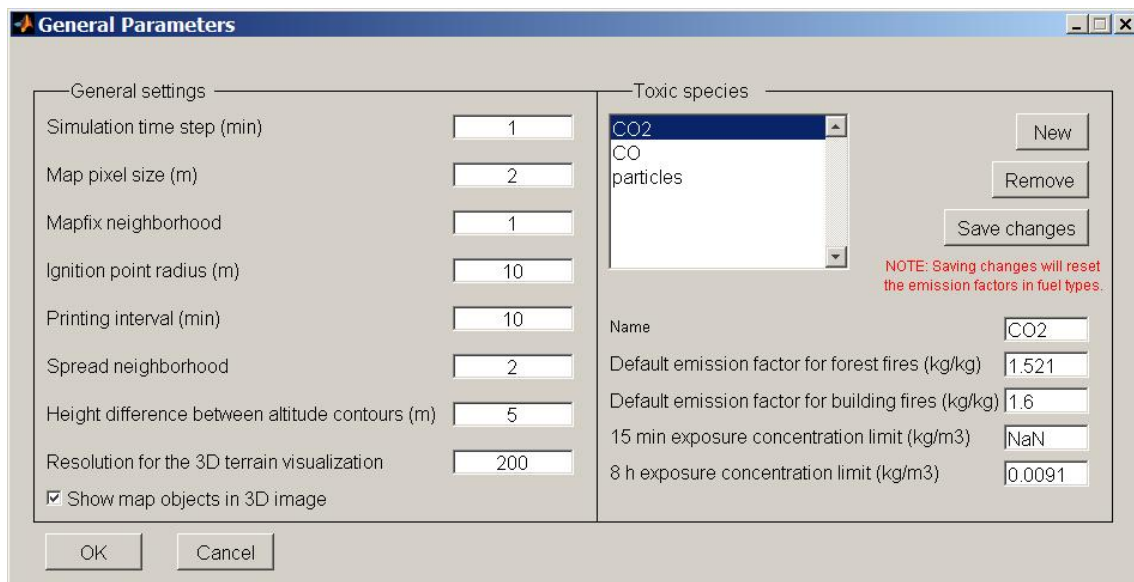


Figure 12. General parameters window.

4.5 Menus

4.5.1 File menu

The file menu contains the following items:

<i>Open Workspace</i>	Opens previously saved workspace. Workspace is a binary file with extension .mat. The workspace files of the future MASIFIRE versions are not necessarily backward compatible.
<i>Save Workspace</i>	Saves the current workspace to a binary file with extension .mat. The workspace file contains all the necessary information for later continuation of the work.
<i>Save As Workspace</i>	Saves the current workspace to a new file.
<i>Read Map</i>	Asks the file name of the map image and reads it using Matlab's imread -function. The requirements for map images are explained in Section 5.2.1.
<i>Load terrain</i>	Loads previously saved terrain information. Terrain files are binary files with extension .ter. The loaded terrain must be compatible with the current map.
<i>Save terrain</i>	Saves the current terrain and the altitude contours to a binary file.
<i>Export time series</i>	Writes the current time series data to a text file. The file contains the following information: Time (s), heat release rate (kW), the x and y-co-ordinates of the fire center point (m), fire area (m ²), emissions of the toxic species (kg/s) and evacuation distances (km) corresponding to each species, if the evacuation was selected from the Main window simulation tools.
<i>Close</i>	Exits MASIFIRE. Please note that the program always exits without asking if the workspace should be saved.

4.5.2 Settings menu

<i>Building setup</i>	Opens the Building setup window (Section 4.3)
<i>Fuel setup</i>	Opens the Fuel setup window (Section 4.2)
<i>General parameters</i>	Opens the General parameters window (Section 4.4)
<i>Grid on</i>	Toggles the visibility of grid on the map.
<i>Show altitude contours</i>	Toggles the visibility of altitude contours on the map.
<i>Highlight map altitudes with colour</i>	Toggles the visualization of altitude information on the map. If selected, high areas are shown as red in the map.
<i>Show building names</i>	Toggles the visibility of building type next to each building object on the map.
<i>Show building wall temperatures</i>	Toggles the visibility of the building wall surface temperature inside each building object on the map. Maximum of the four walls (north, east, south, west) is shown.
<i>Save images</i>	Toggles the saving of the map images during the simulation. If selected, MASIFIRE will save an image of the map, including the fire spread patterns, at every print interval. The jpg-images are saved into a runmasi directory under the current working directory.
<i>Figure menu</i>	Toggles the visibility of Matlab's Figure window menus. These menus contain many useful tools for the controlling of figures.

4.5.3 Tools menu

<i>Calibrate map scale</i>	This tool allows the calibration map pixel size (i.e. scale) by letting the user click two points from the map, and then asking for the distance between the points in meters. This is useful, if the map contains some landmarks with known distance.
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- Resample map image* This tool allows the resampling of the map image in order to increase or decrease the resolution. The tool asks for a new pixel size in meters, and then calculates new map image. After the operation the size of the map has changed in terms of pixels, but the distances are the same. The new pixel size is usually not exactly the one that was asked, but as close to that as possible. Due to the strong dependence of the simulation speed and memory requirements on the size of the map image. It is often useful to decrease the resolution.
- Reduce map colors* This tool can be used to reduce the number of colours on the map. A set of new colours is determined from the original colour palette by the reduction factor given by the user and then all the colours are mapped to the closest colour of the new palette. The user can accept or reject the result. Different values of the reduction factor should be tested. The tool should be used before any simulations have been made.
- Add altitude contour* Asks user to click the points for a new altitude contour. Same operation as pressing 'Add' button on the 'Object tools' panel when Altitude contour is selected from the menu.
- Generate terrain* Calculates the altitude terrain, i.e. the altitude of each map pixel, by interpolating from the altitude contours. Cubical interpolation is used.
- Show terrain* Visualization of the altitude terrain as three-dimensional surface. The altitudes are multiplied by a factor of five to improve the visualization.

5. Operational instructions

5.1 Steps of a typical simulation process

The steps of a typical simulation process are listed below.

1. Have the map image available as a file on your hard disk. See Section 5.2.1 for requirements on the image. It is best to make a separate folder for your simulation.
2. Start Matlab, change to the directory where you have the map, and start MASIFIRE by typing `masifire` to the Matlab prompt (This assumes you have the MASIFIRE installation directory in the Matlab toolbox path.) Alternatively, start `masifire.exe` (not available for MASIFIRE 1.0).
3. Read in the map. See Sections 4.5 and 5.2.
4. If necessary, reduce the map colours using the tool available in Tools menu.
5. Set the map scale (Section 5.2.2). *It is important to scale the map before any other operations below.*
6. Define the altitude terrain by first adding the altitude contours (Section 4.1.3) and then generating the terrain (Section 4.5.3). Check the terrain visually.
7. Set the list of toxic species on the General parameters window (Section 4.4). The species list should always be defined before the definition of fuel and building types because the changing of the species list initializes the emission factors of fuel models and building content types.
8. Define fuels models. You may use the standard fuels that are available when the program starts, define some of your own or load an existing fuel catalog. (Section 4.2).
9. Bind fuel models to the existing map colours. If one vegetation type is dominant in the simulation area, the corresponding fuel model should be made the default fuel. Or if most of the map area is non-combustible, make 'No fuel' the default. See Section 4.1.2 for more information on binding.

10. Bind the map colours that are used for map symbols, altitude contours and texts to the text type appearing in the list of fuel models. If some of the map line types consist of two or more colours, it is best to bind the outmost colour first. Experiment with different MapFix neighbourhoods if the fire spread patterns are not what you expected (Section 4.4).
11. Define new areas on the map using the Outline tool, Section 4.1.2. *It is important to bind the text types before the use of the outline tool.*
12. Define building types. First define the wall and content types, then the actual building types (Section 4.3). If the definitions are available in an existing database, load the database. *It is important to have the forest fuel types defined before the building definition.*
13. Add building on the map (Section 4.1.3).
14. Add ignition source. It may be either one or more ignition point, ignition area or a building serving as ignition source (Sections 4.1.3 and 4.3).
15. Set wind speed and direction (Section 4.1.5).
16. Select the desired additional output: HRR curve, Species emissions or evacuation distances (Section 4.1.4).
17. Set the simulation time in minutes and **run** the simulation (Section 4.1.4).
18. Repeat the steps 14 to 17 as long as needed. However, you may not add other ignition source than ignition points.
19. Export time series, if needed (Section 4.5.1).
20. Save the workspace for later use (Section 4.5.1).
21. Close MASIFIRE (Section 4.5.1).

5.2 Using maps

5.2.1 Map image

Map image is the basis for the whole simulation. The method how the image is obtained is not important, but the quality of the map image is important. Therefore, scanned images should be used with care. The following properties are important for the image:

- The image file should contain three colour components for each pixel (R,G,B).
- The image should contain as few colours as practical to enable the easy but sufficient identification of the vegetation types. If the map colours are continuous or shading, decrease the colour depth using some image processing software. Do not use image formats with lossy compression (typically JPEG) because the lossy compression will alter the colours slightly. Colour reduction tool is available in the Tools menu, Section 4.5.3.
- The resolution should be sufficient so that all the important details can be found, but not too high to keep the simulation times and memory requirements reasonable. The map should not cover too large area. Use image processing software to include only the area of importance. The map resolution can be changed in MASIFIRE using the 'Resample map image' tool available in the Tools menu, Section 4.5.3.

The supported file types are

JPEG	8-bit and 12-bit lossless compressed RGB images
TIFF	24-bit uncompressed images; 24-bit images with packbits compression; and 48-bit RGB images
BMP	24-bit, and 32-bit uncompressed images
PNG	24-bit and 48-bit RGB images.

5.2.2 Setting map scale

Digitized maps consist of pixels, and each pixel has therefore some finite area that it covers. In MASIFIRE, each pixel is used as a cell for the spreading algorithm. It is therefore extremely important that the size of the pixel is correctly set. There are two ways of doing this:

1. User may enter the pixel size in meters to the General parameters window (Section 4.4). This is useful when the map comes from some commercial computer map library, where the pixel size can be found.
2. User may calibrate the map by choosing the calibration tool (Section 4.5.3). User is asked to click on two points on the map, and then type the distance between the points in meters.

5.3 Defining fuels

5.3.1 Choosing one of the standard fuels

The following instructions are taken from BEHAVE 2.0. They give a step-by-step procedure how to choose the best surface fuel model of the 13 standard models. The standard models and their properties are listed in Table 2.

Table 2. The standard surface fuel models [Anderson 1982]. Mo.Ext. is the moisture concentration where the fuel does not burn anymore.

Fuel no	Fuel loading (kg/m ²)				Surface-area-to-volume-ratio (1/m)				Mo.Ext (%)
	1 h	10 h	100 h	Live	1 h	10 h	100 h	Live	
1	0.17	0	0	0	11483				12
2	0.45	0.22	0.11	0.11	9842	358	98	4921	15
3	0.67	0	0	0	4921				25
4	1.12	0.90	0.45	1.12	6562	358	98	4921	20
5	0.22	0.11	0	0.45	6562	358		4921	20
6	0.34	0.56	0.45	0	5741	358	98		25
7	0.25	0.42	0.34	0.08	5741	358	98	5085	40
8	0.34	0.22	0.56	0	6562	358	98		30
9	0.65	0.09	0.03	0	8202	358	98		25
10	0.67	0.45	1.12	0.45	6562	358	98	4921	25
11	0.34	1.01	1.24	0	4921	358	98		15
12	0.90	3.15	3.71	0	4921	358	98		20
13	1.57	5.16	6.29	0	4921	358	98		25
	1 h	=	0... 0.64 cm						
	10 h	=	0.64 ... 2.54 cm						
	100 h	=	2.57 ... 7.62 cm						

Observations

1. Determine the general vegetation type, i.e., grass, brush, timber litter, or slash.
2. Estimate which stratum of surface fuel is most likely to carry the spreading fire. For instance, the fire may be in a timbered area, but the timber is relatively open and the dead grass, not needle litter, would carry the fire. In this case, fuel model 2, which is not listed as a timber model, should be considered. In the same area if the grass is sparse and there is no wind or slope, the needle litter would be the stratum carrying the fire and fuel model 9 would be a better choice.
3. Note the general depth and compactness of the fuel. This information will be needed when using the fuel model key. These are very important considerations, particularly in the grass and timber types.
4. Determine which fuel classes are present and estimate their influence on fire behaviour. For instance, green fuel may be present, but will it play a significant role in fire behaviour? Large fuels may be present, but are they sound or decaying and breaking up? Do they have limbs and twigs attached or are they bare cylinders? You must look for fine fuels and choose a model that represents their depth, compactness, and to some extent, the amount of live fuel and its contribution to fire. Do not be restricted by the fuel model name or category.

Using these observations, proceed through the fuel model key and the descriptions provided by Anderson (1982) to select a model.

Key to the Standard Fire Behaviour Fuel Models

I. PRIMARY CARRIER OF THE FIRE IS GRASS

Expected rate of spread is moderate to high, with low to moderate intensity (flame length).

- A. Grass is fine structured, generally below knee level, and cured or primarily dead. Grass is essentially continuous. Consider fuel model 1.
- B. Grass is coarse structured. above knee level (averaging about 3 feet), and is difficult to walk through. Consider fuel model 3.
- C. Grass is usually under an open timber or brush overstory. Litter from the overstory is involved, but grass carries the fire. Expected spread rate is slower than fuel model 1 and intensity is less than fuel model 3. Consider fuel model 2.

II. PRIMARY CARRIER OF THE FIRE IS BRUSH OR LITTER BENEATH BRUSH

Expected rate of spread and fireline intensity (flame length) is moderate to high.

- A. Vegetative type is southern rough or low pocosin. Brush is generally 2 to 4 feet high. Consider fuel model 7.
- B. Live fuels are absent or sparse. Brush height averages 2 to 4 feet. Brush requires moderate winds to carry the fire. Consider fuel model 6.
- C. Live fuel moisture can have a significant effect on fire behaviour.
 - 1. Brush is about 2 feet high with light loading of brush litter underneath. Litter may carry the fire, especially at low wind speed. Consider fuel model 5.
 - 2. Brush is head high (6 feet) with a heavy loading of dead woody fuel. Very intense fire with high spread rates are expected. Consider fuel model 4.
 - 3. Vegetative type is high pocosin. Consider fuel model 4.

III. PRIMARY CARRIER OF THE FIRE IS LITTER BENEATH A TIMBER STAND.

Spread rate is low to moderate; fireline intensity (flame length) may be low to high.

- A. Surface fuels are mostly foliage litter. Large fuels are scattered and lie on the foliage litter; i.e., large fuels are not supported above the litter by their branches. Green fuels are scattered enough to be insignificant to fire behaviour.
 - 1. Dead foliage is tightly compacted, short needle (2 inches or less) conifer litter or hardwood litter. Consider fuel model 8.
 - 2. Dead foliage litter is loosely compacted long needle pine or hardwoods. Consider fuel model 9.
- B. There is a significant amount of larger fuel. Larger fuel has attached branches and twigs, or has rotted enough that it is splintered and broken. The larger fuels are fairly well distributed over the area. Some green fuel may be present. The overall depth of the fuel is probably below the knees, but some fuel may be higher. Consider fuel model 10.

IV. PRIMARY CARRIER OF THE FIRE IS LOGGING SLASH.

Spread rate is low to high; fireline intensity (flame length) is low to very high.

A. Slash is aged and overgrown.

1. Slash is from hardwood trees. Leaves have fallen and cured. Considerable vegetation (tall weeds) has grown in amid the slash and has cured or dried out. Consider fuel model 6.
2. Slash is from conifers. Needles have fallen and considerable vegetation (tall weeds and some shrubs) has overgrown the slash. Consider fuel model 10.

B. Slash is fresh (0-3 years or so) and not overly compacted.

1. Slash is not continuous. Needle litter or small amounts of grass or shrubs must be present to help carry the fire, but the primary carrier is still slash. Live fuels are absent or do not play a significant role in fire behaviour. The slash depth is about 1 foot. Consider fuel model 11.
2. Slash generally covers the ground (heavier loadings than fuel model 11), though there may be some bare spots or areas of light coverage. Average slash depth is about 2 feet. Slash is not excessively compacted. Approximately one-half of the needles may still be on the branches but are not red. Live fuels are absent, or are not expected to affect fire behaviour. Consider fuel model 12.
3. Slash is continuous or nearly so (heavier loadings than fuel model 12). Slash is not excessively compacted and has an average depth of 3 feet. Approximately one-half of the needles are still on the branches and are red, OR all the needles are on the branches but they are green. Live fuels are not expected to influence fire behaviour. Consider fuel model 13.
4. Same as previous, EXCEPT all the needles are attached and are red. Consider fuel model 4.

5.3.2 Determining the forest biomass

Surface fuels consists of bushes and small trees, understorey vegetation (dwarf shrubs such as lingonberry and bilberry, grasses, mosses and lichen) and litter. A study of the organic matter content of an old spruce forest in Northern Finland determined surface fuel biomass to 1.05 kg/m² [Havas & Kubin 1983]. About 30 % (0.15 kg/m²) of the litter in the old spruce forest was larger than 6 mm in size and about 70 % (0.34 kg/m²) smaller than 6 mm. Figure 13 gives the variation in understorey vegetation biomass in coniferous forests with age of stand.

Canopy fuel consists of foliage and branches. The canopy biomass in an old spruce forest was determined to 2.80 kg/m² [Havas & Kubin 1983]. A tree-dependent estimate is obtained by counting the number of trees per unit area and estimating an average diameter at breast height for the trees. Figure 14 gives an average foliage + branch biomass for one tree. The mass of canopy fuel per unit area can be calculated by multiplying the average biomass of one tree with the number of trees per unit area.

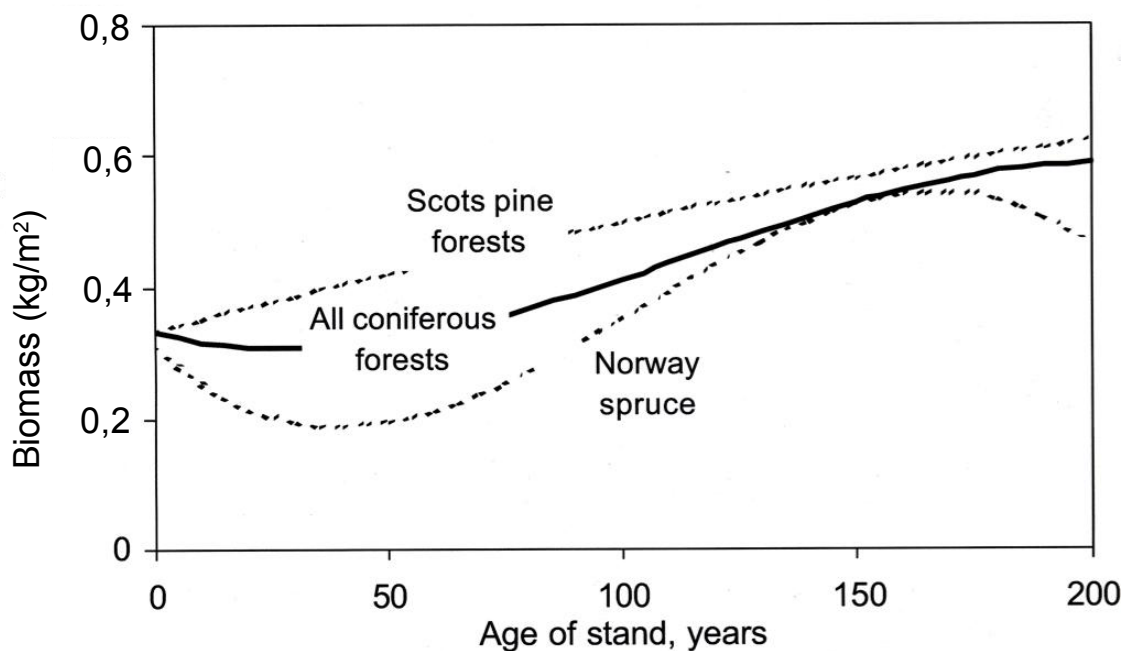


Figure 13. Total biomass of understorey vegetation in coniferous forests (Muukkonen & Mäkipää 2003).

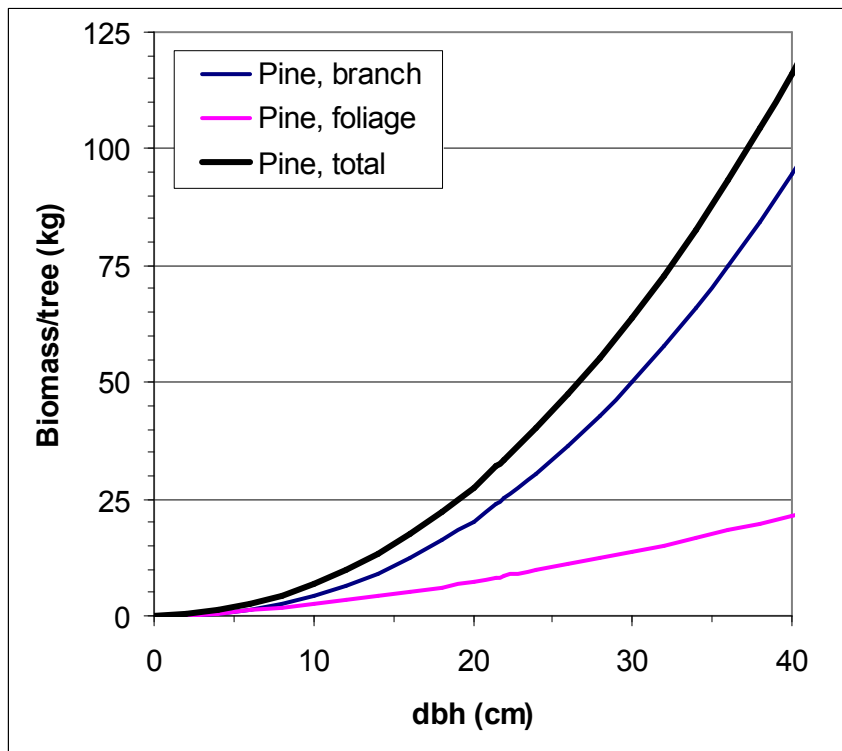
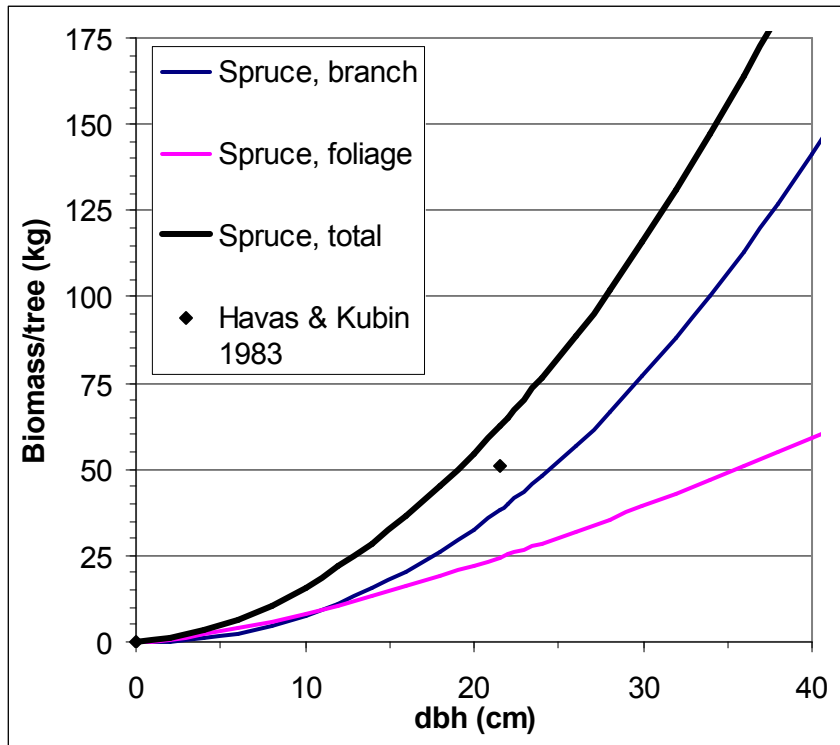


Figure 14. Generalised foliage and branch biomass curves for boreal spruce and pine (Muukkonen 2004). Total = foliage + branch, dbh is diameter at breast height. Estimate for average canopy biomass/tree in an old spruce forest in Northern Finland (Havas & Kubin 1983) is added for spruce.

5.3.3 Creating new fuel models

If none of the standard fuel models appropriately describes the surface fuel, or the crown fires should be included in the simulation, a new model should be created. The easiest way of doing this is by copying the standard fuels to a new fuel catalog, and modifying them. When you have modified any of the fuel model properties, remember to press the 'Apply' button of the Fuel Setup window. Otherwise the changes are not retained when you exit the Fuel Setup. When you have created a new catalog with custom fuel models, you should save the whole catalog on the disk for later use.

6. Summary

Software for Map based Simulation of Fires in Forest-Urban Environment (MASIFIRE) is described. The software can be used for the simulation of fire spread in forests with surface and canopy vegetation, and the spreading of fire from the forest to buildings. The model includes the effects of fuel type, wind, moisture and the shape of the terrain. Model results include the fire spread, total heat release rate, production of toxic species and necessary evacuation area for people. The fire spread algorithm is based on the BEHAVE model developed by the U.S. Department of Agriculture, Forest Service. The features of the user interface and the basic procedure of the use are also described.

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Appendix A: Glossary

This glossary is mainly based on the glossary of Scott & Reinhardt [2001].

Active crown fire — A continuous crown fire in which the entire fuel complex becomes involved and the fire spreads in the canopy fuels.

Available canopy fuel — The mass of canopy fuel per unit area consumed in a crownfire. There is no post-frontal combustion in canopy fuels, so only fine canopy fuels are consumed. We assume that only the foliage and a small fraction of the branchwood is available.

Canopy base height — The lowest height above the ground at which there is a sufficient amount of canopy fuel to propagate fire vertically into the canopy. Canopy base height is an effective value that incorporates ladder fuels such as shrubs and understory trees.

Canopy bulk density — The mass of available canopy fuel per unit canopy volume. It is a bulk property of a stand, not an individual tree.

Canopy fuels — The live and dead foliage, live and dead branches, and lichen of trees and tall shrubs that lie above the surface fuels. See also available canopy fuel.

Continuous crown fire — See active crown fire.

Crown fire — Any fire that burns in canopy fuels.

Fireline intensity — The rate of heat release in the flaming front per unit length of fire front.

Flaming front — The zone at a fire's edge where solid flame is maintained.

Foliar moisture content — Moisture content (dry weight basis) of live foliage, expressed as a percent.

Foliar moisture effect — A theoretical effect of foliar moisture content on active crown fire spread rate.

Fuel model — A set of surface fuel bed characteristics (load and surface-area-to-volume-ratio by size class, heat content, and depth) organized for input to a fire model. Standard fuel models (Anderson 1982) have been stylized to represent specific fuel conditions.

Ground fire — A slow-burning, smouldering fire in ground fuels. Contrast with surface fire. Ground fuels—Fuels that lie beneath surface fuels, such as organic soils, duff, decomposing litter, buried logs, roots, and the below-surface portion of stumps. Compare with surface fuels.

Ignition neighbourhood — A rectangular area of the map around a building where the forest fire may contribute to the heating of the building walls. Width and height of the area are $2 \times \text{IgnitionRadius}$ (100 m at the moment).

MapFix operation — An operation where MASIFIRE tries to determine the actual fuel type of the cells that are marked as 'Text' type. For each 'Text' type cell, the most common fuel type inside the MapFix neighbourhood is applied.

Passive crown fire — A crown fire in which individual or small groups of trees torch out, but solid flaming in the canopy cannot be maintained except for short periods. Passive crown fire encompasses a wide range of crown fire behaviour from the occasional torching of an isolated tree to a nearly active crown fire. Also called torching and candling. See also intermittent crown fire.

Plume-dominated fire — A fire for which the power of the fire exceeds the power of the wind, leading to a tall convection column and atypical spread patterns. The fire spread models used in MASIFIRE do not address plume-dominated fire behaviour. Contrast with wind-driven fire.

Reaction intensity — The heat release rate of fire per unit area.

Surface fire — A fire spreading through surface fuels.

Surface fuels — Needles, leaves, grass, forbs, dead and down branches and boles, stumps, shrubs, and short trees.

Total fuel load — The mass of fuel per unit area that could possibly be consumed in a hypothetical fire of the highest intensity in the driest fuels.

Wind reduction factor — The ratio of the midflame windspeed to the open (6.1-m) windspeed. For convenience of measurement eye-level winds are usually substituted for midflame winds.

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