Project no. FP6-018505

Project Acronym FIRE PARADOX

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D 6.2-3-18-1000 Comparison of contamination models

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RE	Restricted to a group specified by the consortium (including the Commission Services)	
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Reference

Mazzoleni S., Giannino F., Beccarisi L., Ricotta C., 2008. Comparison of fire model tool. Deliverable D6.2-3 of the Integrated project "Fire Paradox", Project no. FP6-018505, European Commission, 43 p.

Executive summary

In the Fire Paradox project, the objective of the work package 6.2 *"Development of a technological platform for integrating the spatial and temporal mechanisms on a completely spatial fire growth tool"* is to develop a software tool able to simulate the propagation of fires at a landscape scale showing, through successive contours drawn on a map, the dynamic evolution of fire spread in <u>any</u> environmental scenario.

Different models and software tools have been proposed to simulate fire behaviour. This paper analyzes and reviews a selection of existing systems (in terms of simulation comparisons and quantitative analysis) in order to discuss and choose some modelling paradigms as bases for the new Fire Paradox propagation modelling software.

Several analyzed models are based on too simplistic physical to be able to simulate the spread of fire across the landscape in a reasonable manner and spatially at high spatial resolution required for the scope of Fire Paradox. In particular they lack consideration of fire-wind feedbacks effects, which we consider mostly important. On the other hand, some tools are a rather complete physical description of the system (including convection effects), but they require (beside a huge use of computational resources) complicated setting of parameters and too detailed data inputs for the Fire Paradox aims.

Our conclusion is that Fire Paradox simulator, compared to existing products, should be characterized by an intermediate level.

The description of fuel remains a critical issue. We suggest that further investigations should be addressed to define fuel properties related to the combustion process separately from the convection and related propagation processes.

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1 Aims

In the Fire Paradox project, the objective of the work package 6.2 *"Development of a technological platform for integrating the spatial and temporal mechanisms on a completely spatial fire growth tool"* is to develop a software tool able to simulate the propagation of fires at a landscape scale showing, through successive contours drawn on a map, the dynamic evolution of fire spread in any environmental scenario.

Different models and software tools have been proposed to simulate fire behaviour. This paper analyzes and reviews a selection of existing systems in order to discuss and choose some modelling paradigms as bases for the new Fire Paradox propagation modelling software.

2 Fire modelling reviews

Since the 1990's, several papers have been published reviewing different types of fire models.

These reviews have some common aspects: definition and classification of different types of fire model; distinction of fire type (surface and crown fire) and some description of the simulation software, whereas no comparison of the related software outputs has been attempted either in a qualitative or statistical way.

A short synthesis of the major published reviews is reported below.

Perry G. (1998). Current approaches to modelling the spread of wildland fire: a review. Progress in Physical Geography, 22(2):222–245.

This is the oldest review that we consider. It classifies fire models as being: physical, semi-physical or empirical, according to the nature of their construction. The benefits and shortcomings of each type of model are considered. Moreover in this paper geographic information systems (GIS) are described as having "great potential for the effective modelling of wildland fire behaviour". There is also some consideration of decision-support systems (DSS) for fire risk evaluation and fire spread simulation.

André J.C.S., Viegas D.X. (2001). Modelos de Propagação de Fogos Florestais: Estado-da-Arte para Utilizadores Parte I: Introducao e Modelos Locais. Silva Lusitana, vol.9, no.2, p.237-265.

André J.C.S., Viegas D.X. (2002). Modelos de Propagação de Fogos Florestais: Estado-da-Arte para Utilizadores Parte II: Modelos Globais e Sistema Informiticos. Silva Lusitana, vol.10, no.2, p.217-233.

This paper (in Portuguese) is divided into two parts. The purpose is to describe the state of the art in fire propagation model domain. In particular, it analyzes the physical principles and modelling strategy, the input and output parameters, and the limits of application. In part I the following classes of fire model are presented: empirical, physical incomplete (and semi-empirical) and physical complete. In part II of the paper, software systems implementing some of the existing fire propagation models are reviewed.

Pastor E., Zarate L., Planas E., and Arnaldos J. (2003). Mathematical models and calculation systems for the study of wildland fire behaviour. Progress in Energy and Combustion Sciene, 29(2):139–153.

This provides a complete review of fire models. In this paper the models are divided into four classes: surface fire spread, crown fire, spotting and ground fire. The last part of the article explores computer software for wildland fire calculations, in particular a brief analysis of different integration with GIS systems is presented (percolation technique, cellular automata, elliptical wave).

Johnston P., Milne G., Klemitz D., (2005). Overview of bushfire spread simulation systems, bushfire report. Bushfire CRC pp. 26.

This paper provides a clear classification and analysis of fire models (theoretical, semi-empirical, empirical). As in Pastor et al., the following fire model types are proposed: surface fire, crown fire and spotting models. A description of some fire spread simulation software is presented (Farsite, Prometheus, SiroFire, Geofogo, FireStation. Vakalis). A simple comparison of different systems is proposed. The last part of the article gives a brief summary of other research simulation systems.

Simeoni A., Andre J., Calogine D., Cuiñas P., Dupuy J.L., Fernandes P., Larini M., Miranda A., Morvan D., Piñol J.,Sero-Guillaume O. (2006). Eufirelab: Behaviour modelling of wildland fires: Final version of the state of the art. Deliverable D-03-09, EUFIRELAB. pp. 44.

This article is the final version of some intermediate deliverables of EUROFIRELAB project. In this paper the scientific group explores the empirical (e.g. Australian, Canadian and European approaches) and physical modeling approach for modeling wildland fire behavior. For empirical models, the authors analyze the required input data of these empirical models. For physical models, the authors compare the different physical models

The third part of the document is dedicated to a complete review of the smoke dispersion models divided thus: research models, planning models and screening models.

Sullivan A. (2007). A review of wildland fire spread modelling, 1990-present, 1: Physical and quasi-physical models. arXiv: arXiv:0706.3074v1 [physics.geo-ph] 28 Jun 2007. pp 42.

Sullivan A. (2007). A review of wildland fire spread modelling, 1990-present 2: Empirical and quasi-empirical models. arXiv:0706.4128v1 [physics.geo-ph] 28 Jun 2007. pp 32.

Sullivan A. (2007). A review of wildland fire spread modelling, 1990-present 3: Mathematical analogues and simulation models. arXiv:0706.4130v1 [physics.geo-ph] 28 Jun 2007. pp 29.

This is the most exhaustive review that we consider (about 100 pages). The fire models are divided in three categories: Physical and quasi-physical, empirical and quasi-empirical, mathematical analogues and simulation models. For each category, a complete list of systems is presented and described.

In all reviews, the models are compared in qualitative terms, whereas simulation comparisons and quantitative analysis are completely missing.

3 Integration of wind models

This document is strictly correlated with D6.3-5 deliverable written by Duncan Heathfield, World in a Box Finland OY, Finland and Morten Nielsen, Risø National Laboratory, Denmark subcontracting of partner UNINA. The D6.3-5 is a complete and exhaustive analysis on "Wind models for fire simulation modelling in Fire Paradox". We suggest to read these two deliverables together.

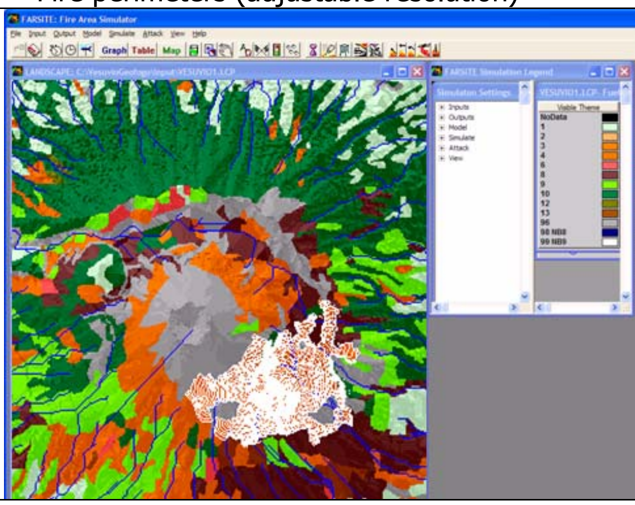
4 Summary of software characteristics

This part of document analyzes some of the major fire behaviour simulators. In particular we analyzed the more important system tools of semi-empirical and physical modelling approach:

1. Farsite
2. Firestation
3. Prometheus
4. Geofogo
5. Fire ModelMed
6. Firetec
7. CAWFE

These systems are compared according to the model implemented, the type of input and output, the user interface, Moreover some attention has been placed on the presence of an atmospheric model and the feedback between fire and wind. A synthetic form is presented for each analyzed software.

4.1 Farsite

Name	Farsite
Hardware Requirements	Memory 64MB,1 Processors Pentium III or IV or later, Free hard drive space: 500MB, Display resolution: 800x600
Software Requirements	Windows Operating System
User Interface	Easy to use, graphical user interface
Type of model	Semi-empirical Model
Intended Use	To simulate the spread and behaviour of wildland fire.
Required Inputs	GIS (grid maps): • Standard/custom fuel types • Elevation • Slope • Aspect • Canopy cover Additional (time series and grid maps): • Temperature • Relative humidity • Wind speed and direction • Canopy characteristics
Output	Maps of: • Fire behaviour • Fire perimeters (adjustable resolution)
Snap-Shot Output	
Simulation time step	You can set a time step between 1 minute and 6 hours but a value less than 1 hour is better.
Simulation time	There is no limit on the time of simulation.
Computational Time	Computational time is much shorter than real time.
Pixel Resolution	The resolution limit is the computer memory; it depends on the availability of data.
Map Resolution	The resolution limit is the computer memory; it depends on the availability of data.
Input Wind	Speed and Direction wind. The wind speed and direction are

	uniform over the whole area.
Wind Model	No
Feedback fire - wind	No
Simulation approach	Elliptical wave propagation
Typology of fire	• Surface Fire Model(Rothermel) • Crown fire (Van Wagner 1979) • Spotting (Albini 1979)
Contact Address	mfinney@fs.fed.us
Web Page	http://farsite.org ftp://fire.org/pub/farsite4b/
Software availability	Free, download from ftp://fire.org/pub/farsite4b/

References:

ftp://fire.org/pub/farsite4b/

User's Manual of Farsite

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

Finney, Mark A. 1999. Spatial Modeling of Post-Frontal Fire Behavior. Final Report RMRS-99557-RJVA, Missoula, MT: Systems for Environmental Management. 8 p.

Keane, Robert E.; Mincemoyer, Scott A.; Schmidt, Kirsten M.; Long, Donald G.; Garner, Janice L. 2000. Mapping vegetation and fuels for fire management on the Gila National Forest Complex, New Mexico, [CD-ROM]. Gen. Tech. Rep. RMRS-GTR-46-CD. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 126 p.

Scott, Joseph H.; Burgan, Robert E. 2005. Standard fire behavior fuel models: a comprehensive set for use with Rothermel's surface fire spread model. Gen. Tech. Rep. RMRS-GTR-153. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station; 72 p.

Stratton, Richard D. 2004. Assessing the Effectiveness of Landscape Fuel Treatments on Fire Growth and Behavior. Journal of Forestry, Oct./Nov., vol. 102, no. 7, pp. 32-40.

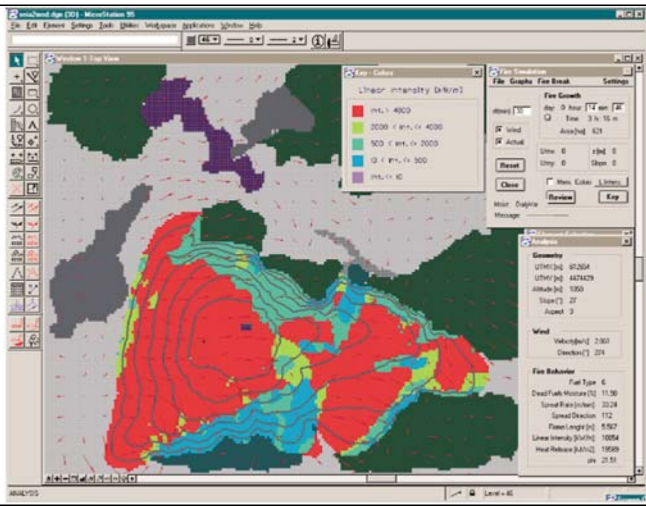
van Wagtendonk, J. W. 1996. Use of a Deterministic Fire Growth Model to Test Fuel Treatments. In Sierra Nevada Ecosystem Project: Final report to Congress, vol. II, chap. 43. Davis: University of California, Centers for Water and Wildland Resources.

Finney, M.A. 1994. Modeling the spread and behavior of prescribed natural fires. Proc. 12th Conf. Fire and Forest Meteorology, pp138-143.

Finney, M.A. and K.C. Ryan. 1995. Use of the FARSITE fire growth model for fire prediction in US National Parks. Proc. The International Emergency Mgt. and Engineering Conf. May 1995 Sofia Antipolis, France. pp 186-

Finney, M.A. and P.L. Andrews. 1996. The FARSITE fire area simulator: fire management applications and lessons of summer 1994. Proc. Intr. Fire Council Mtg. November 1994, Coer D'Alene ID. in press

4.2 Firestation

Name	FireStation
Hardware Requirements	Laptop or desktop IBM-compatible PC, Pentium II or higher processor recommended, 64 Mbytes of RAM minimum, VGA/SVGA colour display.
Software Requirements	Microstation 95 or later (It's a CAD platform from Bentley Company) Microsoft Windows 95 or later.
User Interface	User friendly
Type of model	Semi-empirical Model
Intended Use	Support decision-making on forest and fire management activities at a local scale. Nevertheless, the system also incorporates a fire danger rating system.
Required Inputs	GIS: • Standard/custom fuel types • Elevation Additional: • Temperature • Relative humidity • Fuel moisture (optional) • Wind readings by meteo stations.
Output	Maps of: • Wind speed • Wind direction • Spread rate • Fireline intensity • Flame length, • Heat/unit area • Reaction intensity • Fire perimeter • FWI indices.
Snap-Shot Output	

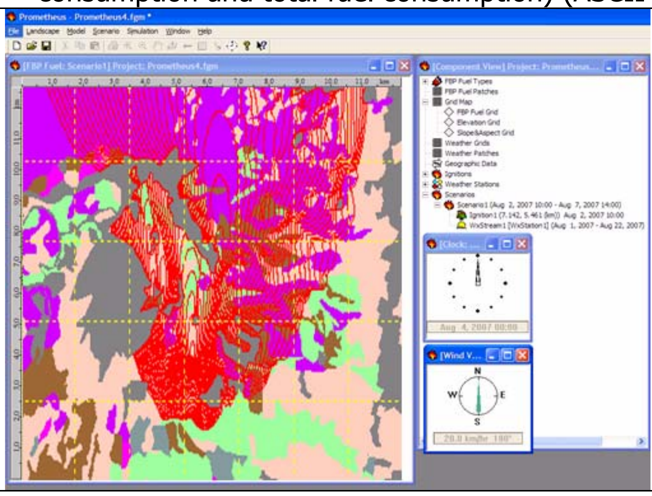
Simulation time step	The time step is provided by the fire growth calculation.The time increment is not constant: it is equal to the time the fire takes to go from a cell to its neighbour.
Simulation time	There is no limit on the time of simulation.
Computational Time	Computational time is much shorter than real time. It depends on the fuel characteristics (fire rate of spread). The computer calculates a certain number of new fire cells per second, depending on the processor speed. Typically, a 2h of real fire may take 1 minute of computation.
Pixel Resolution	The resolution limit is the computer memory; it depends on the availability of data concerning vegetation.
Map Resolution	It depends on the availability of data concerning vegetation.
Input Wind	Wind readings by meteo stations.
Wind Model (actually you get to choose between them)	• NUATMOS Model • CANYON Model (Canyon is a full computational fluid dynamics model and if you are running that then your runs will take much longer.)
Feedback wind-fire	No
Simulation approach	Cellular Automation
Typology of fire	Surface Fire Model (Rothermel)
Contact Address	Antonio M.G. lopes, dipartimento di ingegneria meccanica, Università della Coimbra, Portugal. E-mail: antonio.gameiro@dem.uc.pt
Web Page	http://www.adai.pt
Software availability	Contact the author for information

References:

Manual Firestation

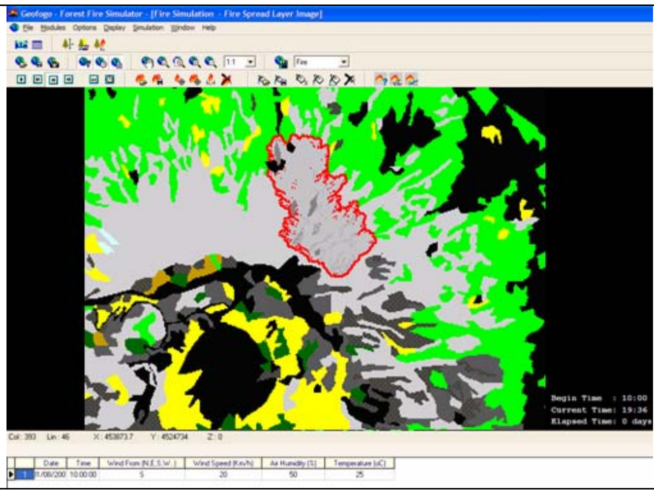
[Lopes et al., 2002] Lopes, A. M. G., Cruz, M. G., and Viegas, D. X. (2002). FireStation - an integrated software system for the numerical simulation of fire spread on complex topography. Environmental Modelling & Software, 17:269-285.

4.3 Prometheus

Name	Prometheus (version 4.4)
Hardware Requirements	Memory: 128MB RAM (512MB RAM is recommended) Hard Drive Space : 250MB
Software Requirements	Operating systems: • Microsoft Windows 2000/XP • Windows Server 2003
User Interface	User friendly
Type of model l	Semi-empirical Model
Intended Use	To simulate fire spread across a landscape on an hourly or daily basis. Fire management
Required Inputs	• FBP fuel type grid (Grid ASCII file) • FBP fuel type lookup table (ASCII text file) • Projection file (ESRI file format) for the FBP fuel type, DEM, slope and aspect Grids. • Fire ignition point, fire ignition line or fire ignition polygon (interactive screen input, • Generate ASCII file or Shapefile) • Weather stream (manual or ASCII data file import)
Output	• Fire perimeter (Graphical, Generate ASCII file, Shapefile) • Fuel breaks (Generate ASCII file, Shapefile) • Modified FBP fuel type Grid (Grid ASCII file) • FBP fuel type lookup table (ASCII text file) • Statistics View (ASCII text file) • Weather Stream (ASCII text file) • FBP output (fire intensity, rate of spread, surface fuel consumption, crown fuel • consumption and total fuel consumption) (ASCII Grids)
Snap-Shot Output	
Simulation time step	Determine the optimal intervals that should be used based on the resolution of the fuel grid and the weather and terrain

	conditions.
Simulation time	There is no limit on the time of simulation.
Computational Time	Computational time is much shorter than real time.
Pixel Resolution	Any cell size
Map Resolution	The model can use any resolution
Input Wind	Speed and Direction (Grid ASCII file format). It is possible to provide a time series of grids.
Wind Model	No
Feedback fire – wind	No
Simulation approach	Elliptical wave
Typology of fire	Surface Fire Model (FBP Canadian Forest Fire Behavior Prediction)
Contact Address	Cordy Tymstra - Prometheus Project Leader Cordy.Tymstra@gov.ab.ca
Web Page	http://www.firegrowthmodel.com
Software availability	Free, download from http://www.firegrowthmodel.com
References: User Manual Prometheus Prometheus on-line help version 4.5.0 http://www.firegrowthmodel.com	

4.4 Geofogo

Name	Geofogo
Hardware Requirements	Memory 32MB, 1 Processor 80486.
Software Requirements	Microsoft Windows95/98 or WindowsNT or later.
User Interface	User friendly
Type of model	Semi-empirical Model
Intended Use (why do you do simulation?)	The program is developed for the prevention of fires and is designed to support the management of forest areas. The program can also be used in strategic planning and the fight for education.
Required Inputs	• Topography (Slope Map and Aspect Map) • Fuel model Map and Leaf Area Index Map • Wheather
Output	Map of • Fire spread with burning severity. • Rate of spread • Fire line intensity
Snap-Shot Output	
Simulation time step	It is cellular automata approach, in 1 time step the fire can propagate just in the neighbour cells
Simulation time	There is no limit on the time of simulation.
Computational Time	Computational time is much shorter than real time.
Pixel Resolution	The resolution limit is the computer memory; it depends on the availability of data.
Map Resolution	All operations on images are much faster the smaller the area to study the system of the simulator is optimized to work with images / map with a grid of cells until 1024 by 1024 cells.
Input Wind	Wind speed and direction (Time Series)
Wind Model	No
Feedback fire - wind	No

Simulation approach	Cellular Automation
Typology of fire	Surface Fire Model (Rothermel)
Contact Address	Project coordinator Maria José Vasconcelos maria.perestrelo@gmail.com
Web Page	http://geofogo.igeo.pt/
Software availability	Free, download from http://geofogo.igeo.pt/

References:

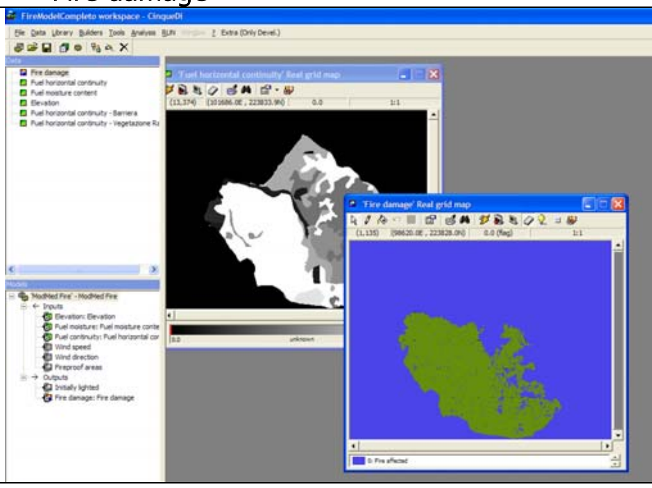
http://geofogo.igeo.pt/

User Manual Geofogo software

Vasconcelos M. J. P.; Gonçalves A.; Catry F. X.; Paúl J. U.; Barros F. A working prototype of a dynamic geographical information system. International Journal of Geographical Information Science, Volume 16, Number 1, 1 January 2002 , pp. 69-91(23)

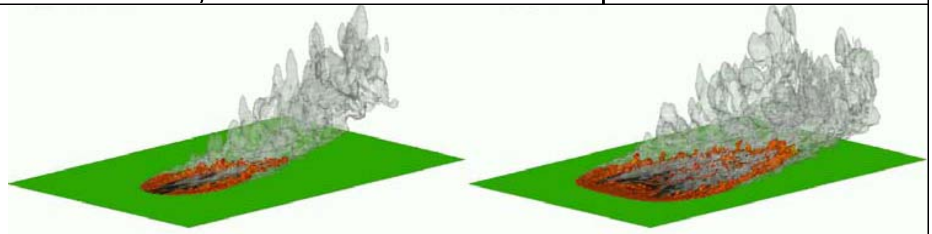
Vasconcelos, M. J. P., Catry, F. X., Gonçalves, A., Uva, J. S. (2001). "Application of Geofogo in Central Portugal". Proceedings of the Workshop - Tools and methodologies for Fire Danger Mapping, 90-105,UTAD, Vila Real.

4.5 ModMed Fire

Name	ModMed Fire
Hardware Requirements	Memory: 128MB RAM (512MB RAM is recommended) Hard Drive Space : 250MB
Software Requirements	Microsoft Windows95/98 or WindowsNT or later.
User Interface	User friendly
Type of model	Semi-empirical Model
Intended Use (why do you do simulation?)	The program is developed for research and teaching purpose in the EU project ModMED
Required Inputs	Map of • Elevation map • Fuel moisture content • Fuel horizontal continuity
Output	Map of • Fire damage
Snap-Shot Output	
Simulation time step	It is cellular automata approach, in 1 time step the fire can propagate just in the neighbour cells
Simulation time	There is no limit on the time of simulation.
Computational Time	Computational time is much shorter than real time.
Pixel Resolution	The resolution limit is the computer memory; it depends on the availability of data.
Map Resolution	The resolution limit is the computer memory; it depends on the availability of data.
Input Wind	Map of Wind speed Wind direction
Wind Model	No
Feedback fire - wind	No
Simulation approach	Cellular Automation

Typology of fire	Surface Fire Model (Rothermel)
Contact Address	Project coordinator prof. Stefano Mazzoleni stefano.mazzoleni@unina.it programmer Duncan Heatfield duncan.heathfield@worldinabox.eu
Web Page	http://www.ecoap.unina.it
Software availability	Free, contact the authors
References: S. Mazzoleni, C. Legg (eds) (2001) ModMED: Modelling Mediteterranean Ecosystem Dynamics, Final Report ModMED Projecte, EU-DGXII Enviromental (IV) Framework, ENV4-CT97-0680.	

4.6 Firetec

Name	Firetec
Hardware Requirements	Actually the software run on 64 processors computer cluster
Software Requirements	Cluster operating systems
User Interface	No GUI.
Type of model	Physics - based transport model.
Intended Use (why do you do simulation?)	To simulate the constantly changing, interactive relationship between fire and its environment.
Required Inputs	"For each simulation with HIGRAD/FIRETEC, there are numerous input data that must be supplied to describe the initial state and the boundary conditions." In particular three dimensional mesh file of vegetation state condition.
Output	Out of all variables is on the same three dimensional mesh. In particular temperature value, rates of spread, oxygen concentration and wind value, for each node in each time step.
Snap-Shot Output	
Simulation time step	typically a few seconds (0,002 s)
Simulation time	Strictly function of the settled problem and machine configuration. Typically: maximum some days.
Computational Time	Strictly function of the settled problem and machine configuration. Computationally intensive. Simulation can take 1 or 2 days on 64 processors and is typically significantly shorter than an hour.
Pixel Resolution (cell size)	Horizontal resolution is typically 2 m, and vertical is near 1.5 m.
Map Resolution	Strictly function of machine configuration. Max 1000 m X 1000 m
Input Wind	Wind boundary condition.
Wind Model (atmospheric model)	HIGRAD
Feedback fire - wind	Yes - completely coupled fire model with atmosphere
Simulation approach	CFD – Computer Fluid Dynamic
Typology of fire	• Surface fire (Rothermel Model) • Crown fire • Spotting fire

Contact Address	Rodman Linn : rrl@lanl.gov
Web Page	
Software availability	No

References:

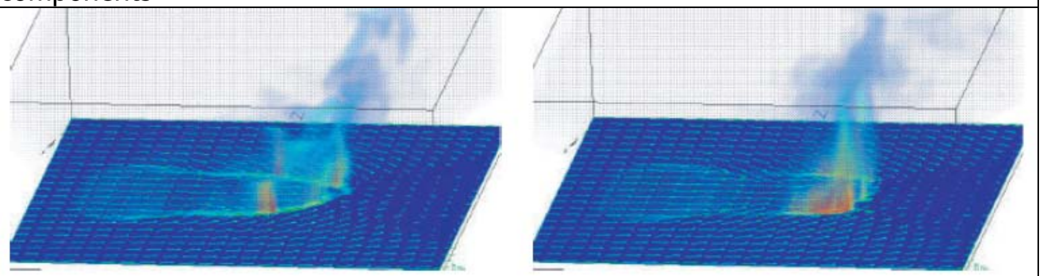
Linn, R., Cunningham, P. (2005) "Numerical simulations of grass fires using a coupled atmosphere-fire model: Basic fire behavior and dependence on wind speed," *J. Geophysical Research*, to appear.

Linn, R., Cunningham, P. (2007) "Numerical simulations of grass fires using a coupled atmosphere-fire model: Dynamics of fire spread", *J. Geophysical Research*.

Rodman Linn, Judith Winterkamp , Jonah J. Colman, Carleton Edminster and John D. Bailey (2005) "Modeling interactions between fire and atmosphere in discrete element fuel beds", *Intl. J. Wildland Fire.*

Rodman Linn , Judith Winterkamp , Carleton Edminster , Jonah J. Colman and William S. Smith .(2007) "Coupled influences of topography and wind on wildland fire behaviour", *Intl. J. Wildland Fire.*

4.7 CAWFE

Name	CAWFE (Coupled Atmosphere-Wildland Fire-Environment) model
Hardware Requirements	
Software Requirements	Unix operating systems. NCAR graphics is helpful for plots and analysis.
User Interface	Unix system program with no GUI.
Type of model	"The modeling system is composed of a three-dimensional atmospheric prediction model that has been two-way coupled with an empirical fire spread model"
Intended Use	To simulate the constantly changing, interactive relationship between fire and its environment.
Required Inputs	• Fuel - Surface and canopy fuels - Mass/area - Physical characteristics • Topography • Large-scale weather forecasts
Output	1-byte files with state variables like potential temperature, pressure, wind components
Snap-Shot Output	
Simulation time step	It depends on the grid configuration, resolution, and phenomena being studied. Perhaps 1/3 sec to 2 minutes is recommended.
Simulation time	It depends on the grid configuration, resolution, and phenomena being studied.
Computer Time	That depends on the configuration, size of the problem, and resolution. Typically: maximum some days.
Pixel Resolution	The fire simulations can be done with grid points perhaps 10 meters apart with the lowest vertical grid point at 5 m or so
Map Resolution	Strictly function of machine configuration. Max 10000 m X 10000 m
Input Wind	
Wind Model	Solve prognostic fluid dynamics equations of motion for air momentum, a thermodynamic variable, water vapor and precipitation on a finite difference grid.
Feedback fire - wind	Yes - completely coupled fire model with atmosphere
Simulation	CFD – Computer Fluid Dynamic

approach	Finite difference grid elements
Typology of fire	• Surface fire (Rothermel Model) • Crown fire
Contact Address	janicec@ucar.edu
Web Page	
Software availability	No
References: Clark, T. L., Coen, J., Latham, D.: Description of a coupled atmosphere-fire model, Intl. J. Wildland Fire, 13, in print (2004).	

5 Software simulations

5.1 General comparison

Given the same initial conditions (fuel, ignition point, and environmental factors), deterministic models do produce the same results in every simulation. Differently, stochastic modelling approaches produce different patterns at each run.

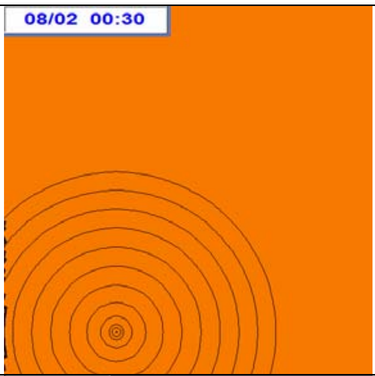
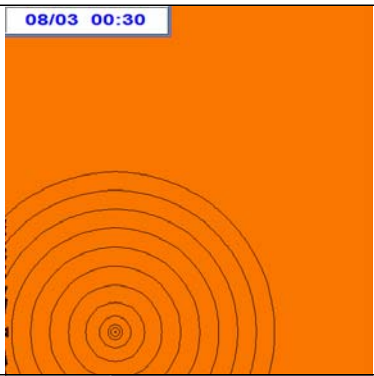
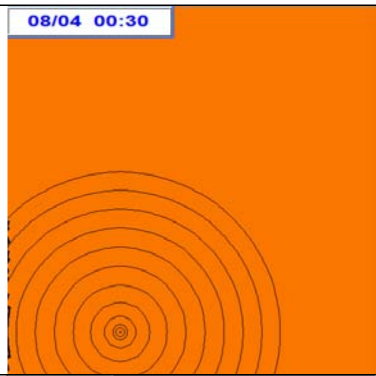
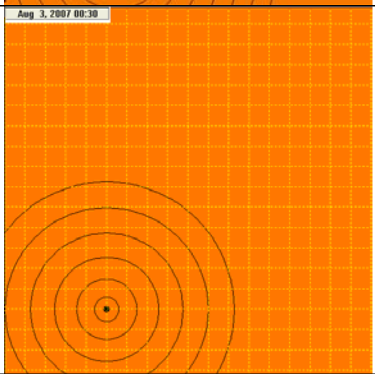
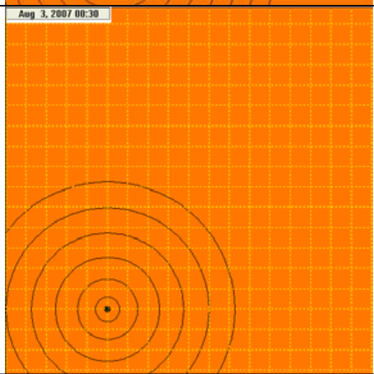
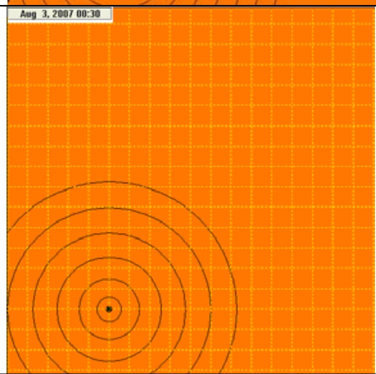
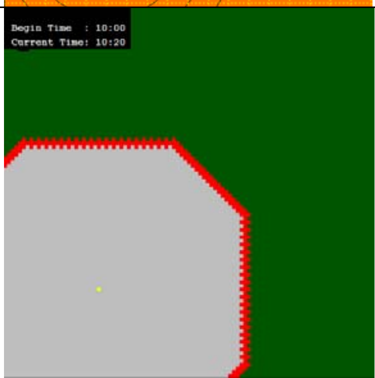
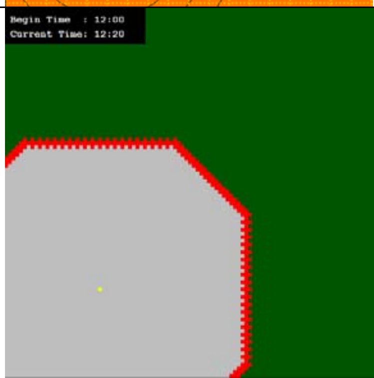
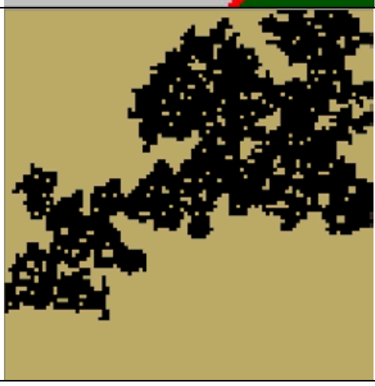
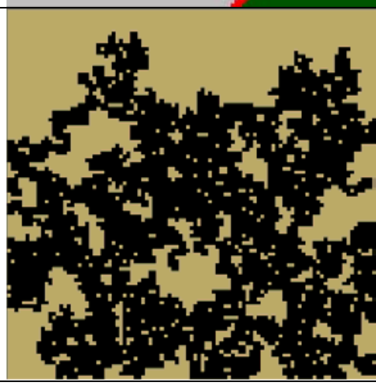
The following tabular pictures show these concepts by a comparative application of different fire propagation software on a homogeneous fuel type.

Farsite and Prometheus are examples of application of wave propagation models, Geofogo is a deterministic cellular automata, while ModMed is based on a stochastic approach.

In the simulation exercise, using a uniform fuel type set at optimal burning condition in terms of moisture content (well above the extinction level) and with no wind, the simulated burning patterns will reflect only the intrinsic law of the propagation algorithm, without effects due to the spatial variability of fuel conditions.

Looking at these figures, besides the obviously different perimeter contours, another major difference between the reported applications is that, in the first three cases, the propagation stops only when the run of the model is interrupted because the fire front never reaches a non-burning area provided the totally homogenous simulated landscape. On the contrary, in the case of stochastic approach some extinction occur also under such conditions.

Moreover, another consequence of these different approaches is that in the deterministic models the burned area is equal to the surface delimited by the fire contour lines, i.e. 100% of the area where fire has propagated. Differently, the probabilistic behaviour does produce in addition to a natural extinction of the fire, also the rise of a fractal pattern which includes scattered unburned areas.

	Simulation 1	Simulation 2	Simulation 3
Farsite			
Prometheus			
Geologo			
ModMed			

The issue of comparing real fires with simulation results is a difficult one and rarely faced in the literature in relation of Mediterranean areas. For example, a comparative study between Farsite results and observed data was done by Arca et al. (2007)[1], whereas real remote sensed data and outputs of percolation models have been comparatively presented in the paper by Caldarelli et al. (2001)[2]. However, no studies are available where the results of a percolation modelling approach have been statistically analyzed versus real fire observations in order to asses their capability to simulate fire behaviour for applied purposes.

In their work, Arca et al. (2007), discuss on the difficulties of obtaining a good fitting between real data and simulated output because of the simplified representation of weather and wind conditions, especially in areas characterized by complex steep terrain. Furthermore, the authors point out the difficulties of calibration of the fuel models.

The following figures are reported from the two above mentioned papers.

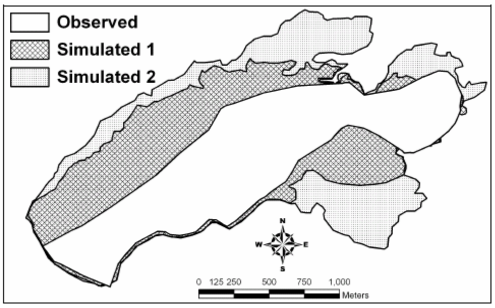


Figure 1 – Comparison between observed and simulated fire areas from the simulation n. 4 (custom fuel model CM28) using raster wind maps (Simulated 1) and constant wind field (Simulated 2) – from Arca et al. 2007.

[1] Arca, Duce, Pellizzaro, Bacciu, Salis and Spano "*Evaluation of Farsite Simulator in a Mediterranean Area*", in Proceedings of the 4th International Wildland Fire Conference, ISBN: 978-84-8014-690-6, Sevilla, Spain, 2007.

[2] Caldarelli, G., Frondoni, R., Gabrielli, A., Montuori, M., Retzlaff, R. and Ricotta, C. (2001) Percolation in real wildfires. Europhysics Letters, 56 :510–516.

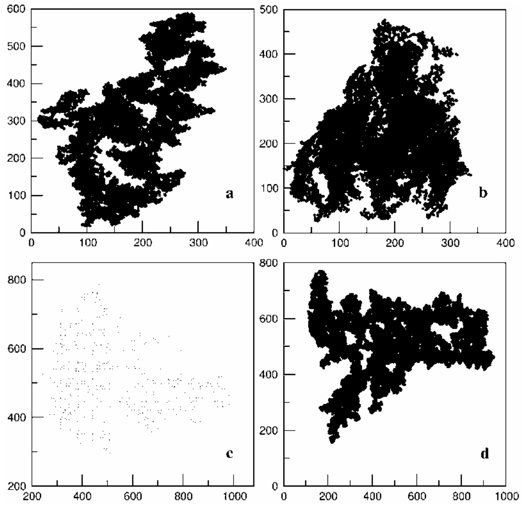


Figure 2 - Binary map of the burnt areas a) for the valley of Biferno, b) for the Penteli wildfire, c) for the Cuenca wildfire. In d) we plot a cluster of Self-Organised Dynamical Percolation whose dimensions are comparable with case c). Each pixel corresponds to an area of 900m^2 – from Caldarelli et al. (2001).

5.2 Effects of fuel spatial pattern

In this section a comparative application of four software tools (Farsite, Prometheus, Geofogo and ModMed Fire) is presented. They were selected as representative of two different approaches (elliptic wave propagation and cellular automata). The models based on CFD have not been considered because of their heavy computational demand and their unfeasible application by end-users in the field of fire fighting.

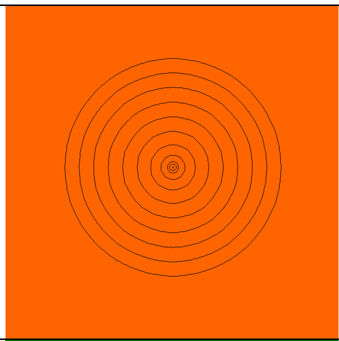
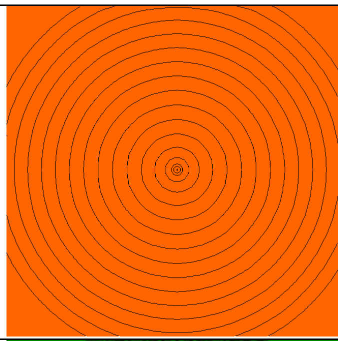
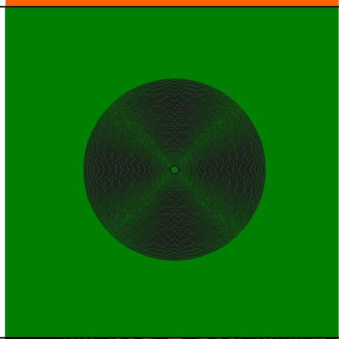
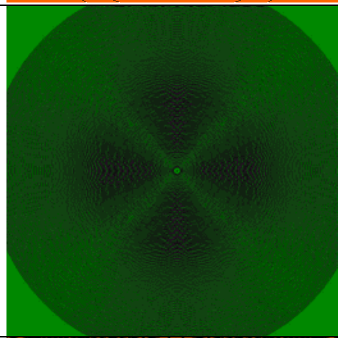
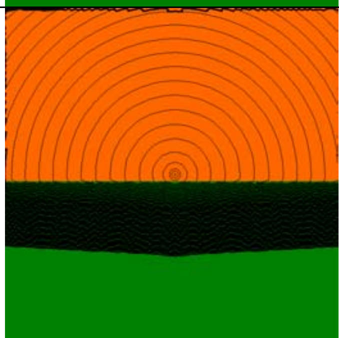
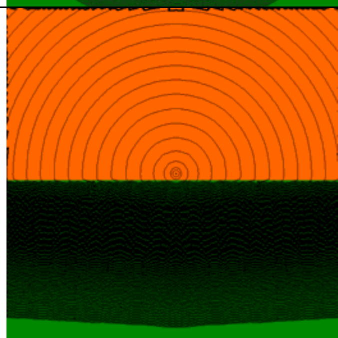
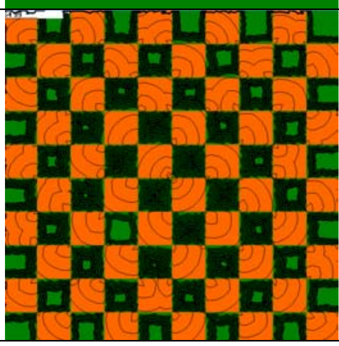
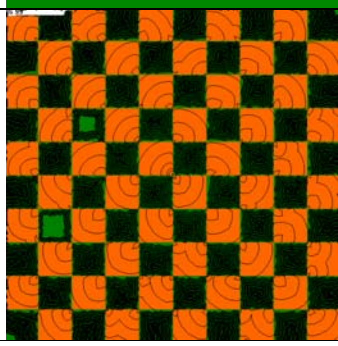
A simple theoretical comparison was designed according to two different fuel types (grass-fast fire propagation and timber–slow fire propagation) and different spatial patterns of their distribution. The spatial resolution is 1 m^2 and time resolution is 5 minutes. Two simulations were run for homogenous fuel conditions while other three with presence of both fuel types with different spatial arrangements: extended border between grass and timber (2 adjacent areas of 5.000 m^2), mixed large resolution mosaic (100 squares of 100 m^2) and mixed fine resolution mosaic (10.000 squares of 1 m^2).

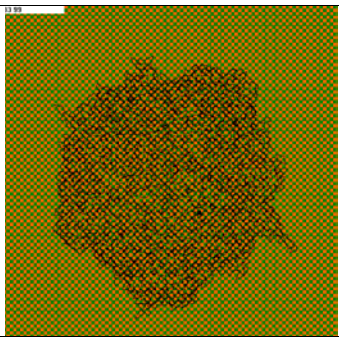
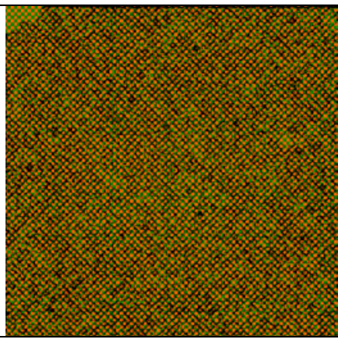
Fuel Type	**Spatial pattern**
Grass	Homogenous
Timber	Homogenous
Grass/Timber	2 adjacent areas of 5.000 m^2
Grass/Timber	100 squares of 100 m^2
Grass/Timber	10.000 squares of 1 m^2

Table 1 – Summary of simulation conditions.

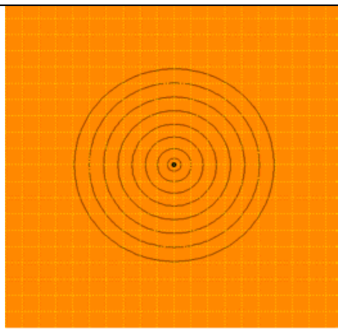
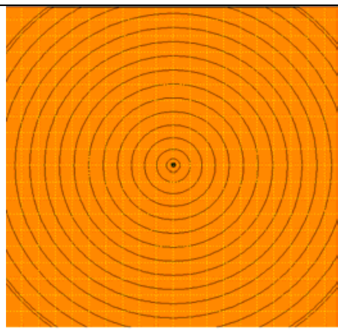
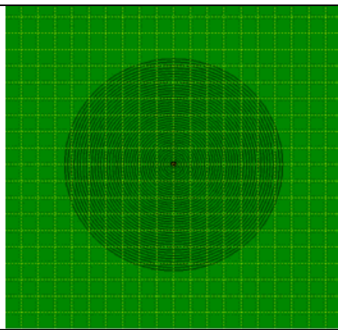
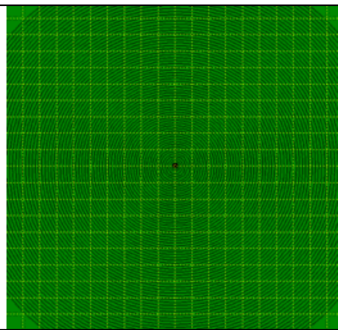
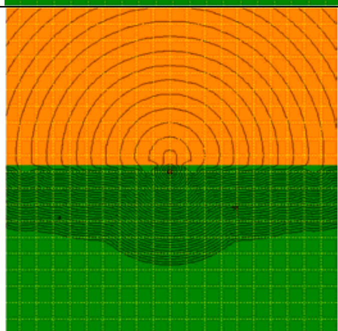
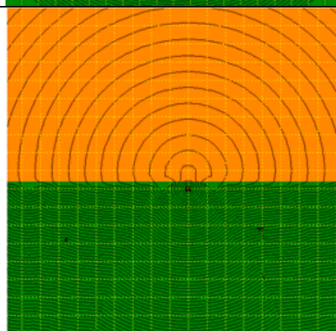
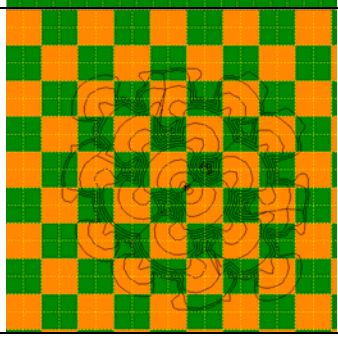
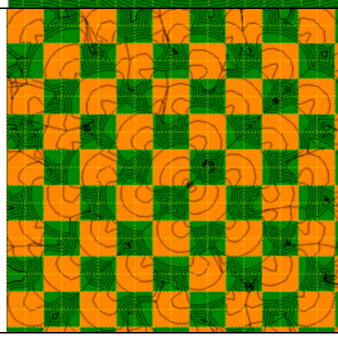
The following tabular figures report the summary of simulation results.

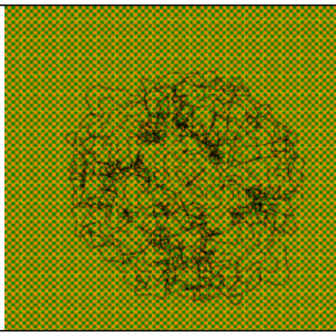
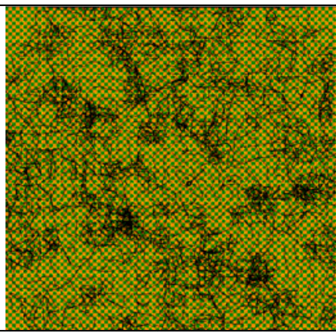
5.2.1 Farsite

	Half Time	Time 90%
Grass		
Timber		
Grass / Timber 2 adjacent areas of 5.000 m^2		
Grass / Timber, 100 squares of 100 m^2		

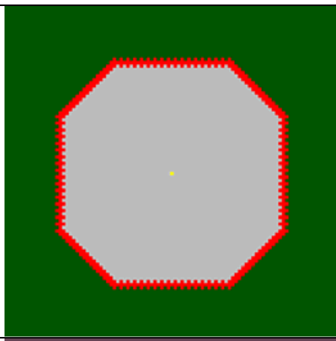
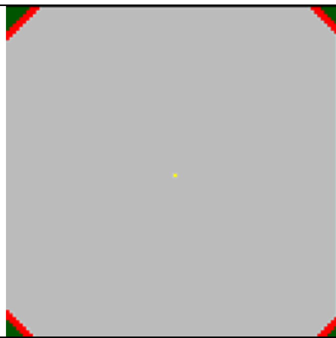
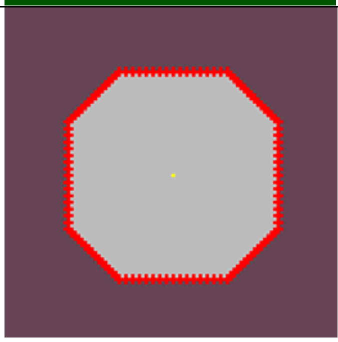
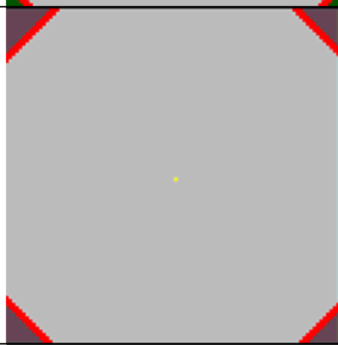
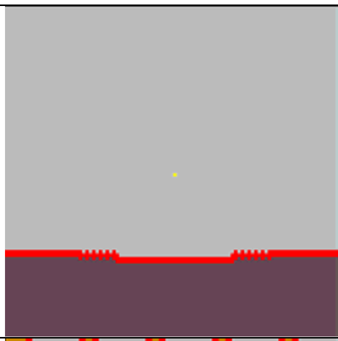
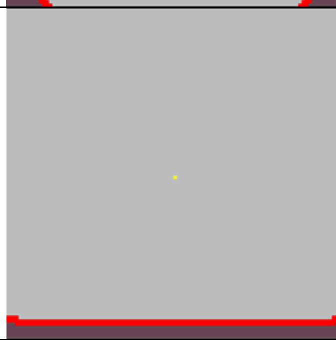
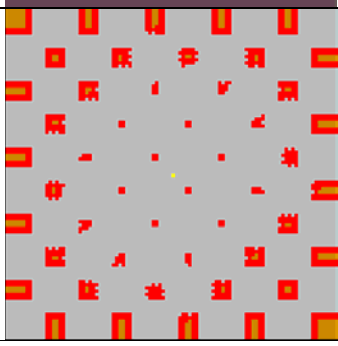
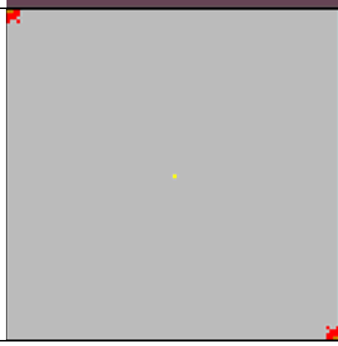
Grass / Timber 100 squares of 100 m^2		

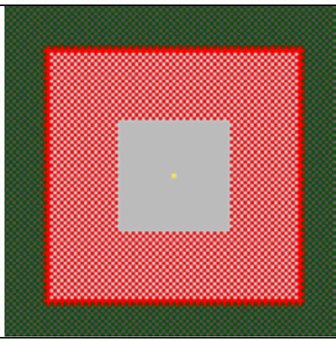
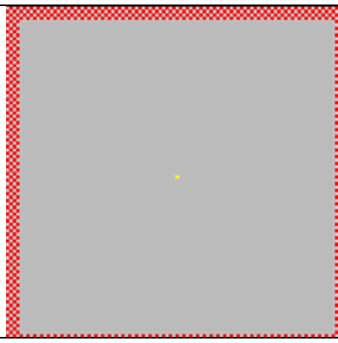
5.2.2 Prometheus

	Half Time	Time 90%
Grass		
Timber		
Grass / Timber 2 adjacent areas of 5.000 m^2		
Grass / Timber, 100 squares of 100 m^2		

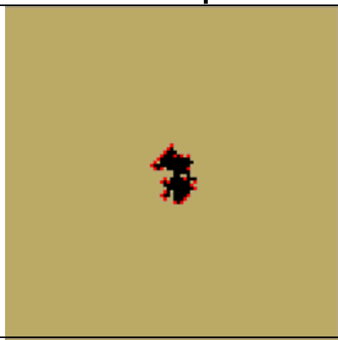
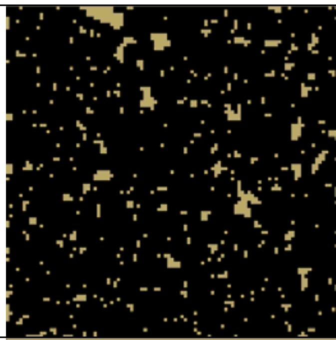
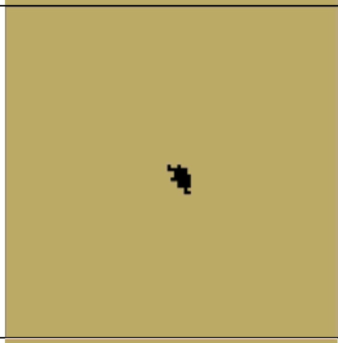
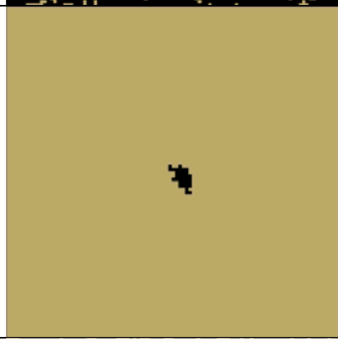
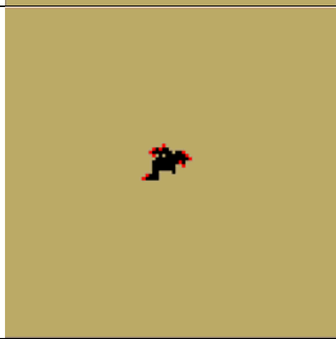
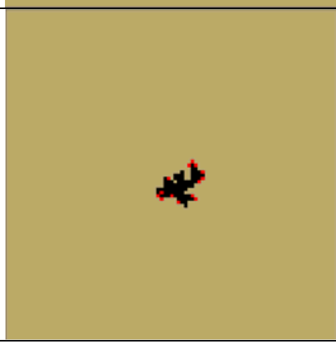
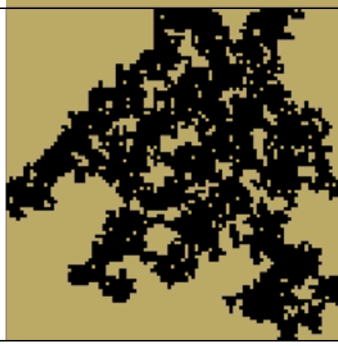
Grass / Timber 100 squares of 100 m^2		

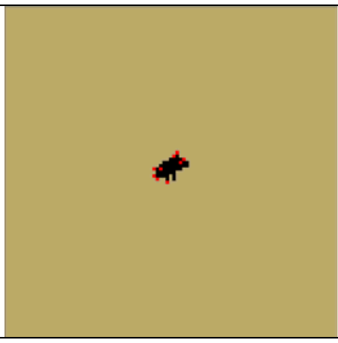
5.2.3 Geofogo

	Half Time	Time 90%
Grass		
Timber		
Grass / Timber 2 adjacent areas of 5.000 m^2		
Grass / Timber, 100 squares of 100 m^2		

Grass / Timber 100 squares of 100 m^2		

5.2.4 ModMed Fire

	Time Step 10	Final Time
Grass		
Timber		
Grass / Timber 2 adjacent areas of 5.000 m^2		
Grass / Timber, 100 squares of 100 m^2		

Grass / Timber 100 squares of 100 m^2		

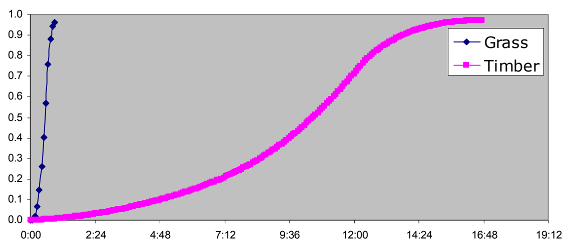
In the case of Farsite and Prometheus tools, it is possible to analyze the numerical results of the simulation exercises by plotting the total burned area versus time.

The following figures show the dynamics of burned area during the model run in two homogeneous fuel type scenarios. In the reported examples the two software produced similar outputs for grass and showed slower propagation speeds when applied to different forest fuels.

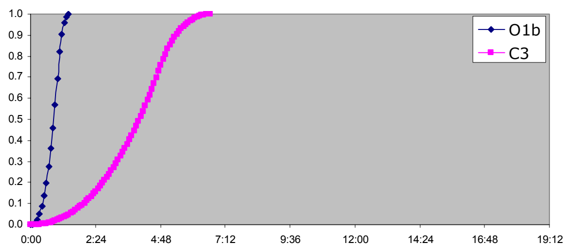
The observed results od spread in timber/C3 reported in the figures below obviously depends on the differences the fuel types used for the two software. However, looking at the effect of the spatial pattern of fuel distributions, it can be noted that Farsite seems more sensible than Prometheus by showing a change of propagation according to the spatial resolution of the fine fuel mosaics.

HOMOGENEOUS FUEL TYPES

Farsite

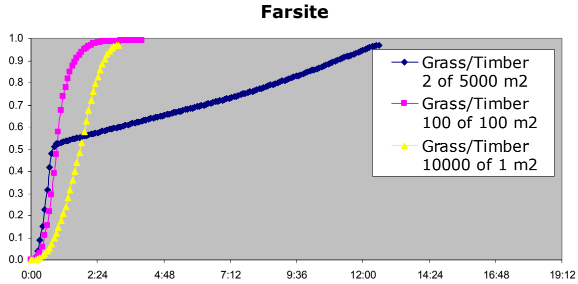


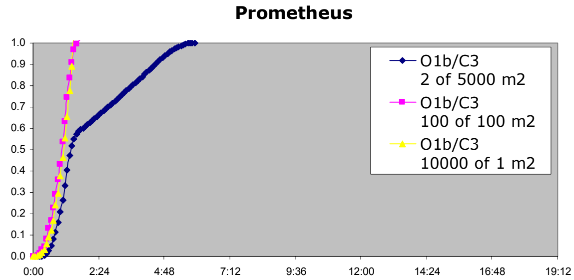
Prometheus



In the example below, reporting simulations on different spatial distribution of fuel type, in the case of the two adjacent areas of 5.000 m^2 (darker blue lines), the qualitative behaviour is similar between the two software still showing the different propagations regimes due to the forest fuel types as discussed above.
However when the propagation occurs in a fragmented simulated fuel distribution, the size of single patches is effecting the rate of propagation only in the case of Farsite. In other words, while Promotheus propagation shows the same speeds in both cases of 100 squares of 100 m^2 and 10000 squares of 1 m^2, Farsite burning is faster with larger patch size.

DIFFERENT SPATIAL PATTERNS OF FUEL TYPES





In conclusion, the resolution of mixed spatial scenarios of fuel types is an issue to be considered with attention because of the possible consequence on the output of propagation speed in the available software tools.

6 Model parameterization

The analysed programs are very complex systems. In this paragraph, we report the complete list of parameters that can be possibly set in the different tools. This is done to emphasize the fact that many settable parameters are not usually controlled by the users despite their major influence on modelling results.

6.1 Farsite[3]

Adjustment Factors	Rate of spread adjustment factors allow the user to use experienced judgment or local data to tune the simulation to observed or actual fire spread patterns. The ***Adjustment Factor*** can be a floating point number (decimal) specifying the multiplier for rate of spread adjustment.
Custom Fuel Model File	
1H, 10H, 100H, LiveH, LiveW	Fuel Loading
1HSAV, LiveHSAV, LiveWSAV	Surface to Volume Ratio
Depth	Fuel Bed Depth
XtMoist	Moisture of Extinction
DHt, LHt	Heat Content, live & dead fuels
Coarse Woody Profile File	
SizeClass	The representative size of the class based on surface to volume ratio.
Loading	Fuel loading of the class (decimal), units are tons/acre or kilograms/hectare
HeatContent	Heat content of the class (integer), units are BTU/lb or joules/kilogram
S/R	Sound or rotten is defined by the density of the fuel (lb/ft3, or kg/m3).
Moist	Moisture content of the size class in percent (integer).
Fire Acceleration	Fire acceleration is defined as the rate of increase in fire spread rate. It affects the amount of time required for a fire spread rate to achieve the theoretical steady state spread rate given 1) its existing spread rate, and 2) constant environmental conditions.
Canopy Characteristics	
Height	The average height of the top of the canopy. Used as a starting point for embers, calculating wind reductions, and computing volume of crown fuels.
Crown Base (CBH)	It is the height to the bottom of the live crown over the area. CBH should incorporate the effects of ladder fuels. Zero is not a valid input for this field.

[3] Farsite Online Help, Firesite v. 4.1.03

Bulk Density (CBD)	It is the density of available crown fuels on a stand or area basis. Zero is not a valid input for this field.
Foliar MC	Foliar Moisture Content, the moisture content of the coniferous crown fuels. Not necessarily the same as live fuel misture.
Diameter	Average DBH of trees expected to torch.
Species	Species of trees expected to torch.
Tolerance	The shade tolerance of the torching trees.

6.2 Prometheus[4]

New Fuel Type	
A	Rate of Spread equation coefficients
B	Rate of Spread equation coefficients
C	Rate of Spread equation coefficients
Q	Proportion of maximum rate of spread at BUI equal to 50
BUIo	Buildup Index
MaxBe	Maximum Buildup effect on spread rate
CBH	Height to live crown base (m)
CFL	Crown fuel load
Weather Stream	
FFMC	Fine fuel moisture code
DMC	Duff Moisture Code
DC	Drought Code

6.3 Geofogo[5]

Fuel Parameters	
NFFL models	Standard National Forest Fire Laboratory fuel models.
1 htr	Accumulated dead 1 hour fuels.
10 htr	Accumulated dead 10 hour fuels.
100 htr	Accumulated dead 100 hour fuels.
C3	It refers to a NFFL standard fuel model.
C4	It refers to a NFFL standard fuel model.
C5	It refers to a NFFL standard fuel model.
C6	It refers to a NFFL standard fuel model.
C7	It refers to a NFFL standard fuel model.
Depth	Fuel bed depth.
Heat	Heat content by category
Moist Extinction	Moisture of extinction of dead fuels.
C11	It refers to a NFFL standard fuel model.
C12	It refers to a NFFL standard fuel model.

[4] Information Report ST-X-3 "Development and Structure of the Canadian Forest Fire Behavior Prediction System" Forestry Canada Fire Danger Group, 1992

[5] Definition of these parameters are not found in Geofogo software documentation. Anyway we presume that some parameters are deduced from Standard National Forest Fire Laboratory fuel models.

C13	It refers to a NFFL standard fuel model.
C14	It refers to a NFFL standard fuel model.

6.4 ModMed[6]

The ModMed Fire model is entirely theoretical. It's up to the user to define the nature of the interactions among the named input phenomena (Fuel Moisture Continuity, Fuel Horizontal Continuity, Wind, Slope) which combine to give the resulting contagion probability between neighbouring grid cells. The type of function used in each case is pre-determined, but the parameters of the function can be provided. These parameters do not immediately correspond to any real-world relationships or concepts such as are usually mentioned in the literature.

Factor Adjustments	
h	Fuel Horizontal Continuity weight
m	Fuel Moisture Continuity weight.
w	Wind weight.
s	Slope weight
Fuel Horizontal Continuity (FHC)	
The linear coefficient.	Parameter of the fire probability function of FHC
The quadratic coefficient.	parameter of the fire probability function of FHC
The cubic coefficient.	parameter of the fire probability function of FHC
Fuel Moisture Continuity (FMC)	
The linear coefficient.	parameter of the fire probability function of FMC
The quadratic coefficient.	parameter of the fire probability function of FMC
The cubic coefficient.	parameter of the fire probability function of FMC
Wind	
Parameter Value	parameter of the fire probability function of wind
Slope	
Parameter Value	parameter of the fire probability function of slope

[6] S. Mazzoleni, C. Legg (eds) (2001) ModMED: Modelling Mediteterranean Ecosystem Dynamics, Final Report ModMED Projecte, EU-DGXII Enviromental (IV) Framework, ENV4-CT97-0680

7 Note on the fuel model approach

The use of fuel models and inherent fuel maps suffer from some constraints related to the relative effectiveness of models (with respect to specific fire growth models and specific geographic ranges) and their accuracy.

Fuel maps are representations of fuel types spatial distributions. Fuel types are defined intrinsically, such as in Prometheus, or as fuel models that are described by sets of average fuel characteristics. A major issue here is if the detail of fuel type mapping is compatible with the accuracy/resolution of the selected fire spread model.

Though it is not a weakness exclusive of this kind of maps, another drawback of fuel maps comes from classification and generalization. Over 20% of fuel map error results from the inherent variability of ecological attributes at the stand level[7] this variability is not expressed in the maps. Obviously, eventual map errors propagate in the fire growth models, affecting the outputs. Moreover, with particular reference to fire growth models, they should require high resolution digital fuel maps, with pixel sizes in the interval 5-30 m[8], if not less; TM, SPOT, AVIRIS, IKONOS or aerial photos are examples of imagery with such high resolution. Since spatial resolution is often inversely related to classification accuracy[9], a general way to improve map accuracy is to increase the fineness of the classification system. This was the Scott and Burgan's work[10], enhancing the former set of 13 standard fire behaviour fuel models[11] of the Rothermel's surface fire spread model (1972) through the development of a new 45 classes set.

However fine the classification system is, inherent fuel maps remain properly empiric representations, then they are subject to the law of relative site constancy[12] accordingly, and can rise problems when attempting to make inferences outside the determined geographic ranges. As example, the Rothermel's model[13] was originally based on North

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[7] Keane R. E., Mincemoyer S. A., Schmidt K. A., Long D. G., Garner J. L., 2000 – Mapping vegetation and fuels for fire management on the Gila National Forest Complex, New Mexico. USDA Forest Service General Technical Report RMRS-GTR-46-CD.

[8] Keane R. E., Burgan R., van Wagtendonk J., 2001 – Mapping wildland fuels for fire management across multiple scales: Integrating remote sensing, GIS and biophysical modeling. International Journal of Wildland Fire, 10: 301-319.

[9] Atkinson P. M., Foody G. M., 2002 – Uncertainty in remote Sensing and GIS: Fundamentals. In: Foody G. M., Atkinson P. M. (Eds.) - Uncertainty in remote Sensing and GIS. John Wiley & Sons Ltd: 1-18.

[10] Scott H. J., Burgan R. E., 2005 – Standard Fire Behavior Fuel Models: A Comprehensive Set for Use with Rothermel's Surface Fire Spread Model. USDA Forest Service General Technical Report RMRS-GTR-153.

[11] Albini F. A., 1976 – Estimating wildfire behavior and effects. USDA Forest Service General Technical Report INT-30.

[12] Guisan A., Zimmermann N. E., 2000 – Predictive habitat distribution models in ecology. Ecological Modelling, 135: 147-186.

[13] Rothermel R. C., 1972 – A mathematical model for fire spread predictions in wildland fuels. USDA Forest Service Research Paper INT-115.

American vegetation; its application to Mediterranean vegetation did not give success immediately, because of the difficulty of calibration process[14].

Fuel models describe average characteristics and do not provide any information of spatial relations between fuel components at finest scales. Tools such as BehavePlus and FARSITE can have problems of reliable assessment fire behaviour because do not consider the complex and dynamic nature of fire-fuel and fire-atmosphere interactions[15] (e.g. lack of representation of back fire applications). Instead, physics-based numerical fire behaviour models (such as FIRETEC, WFDS), that rely on fine scale spatially explicit fuels inputs, should theoretical bring to better predictions of fire behaviour and potentially facilitate analyses at multiple scales. However these latter models because of input parameterization problems and computational constrains not necessary can conduce to better predictions of fire behaviour in real landascape applications.

It is clear that fuel descriptions are dependent on the capabilities of the fire models to use the information and the ability to reliably know the fuels across large landscapes. Unless there is a practical fire model that can use very detailed information, highly detailed fuel description will be wasted. In other words the problem is that fire models that use very detailed fuel data are not practical and it remains to be shown if they even can generate adequate fire predictions.

In practice there has been little if not considerations of the relations between the spatial resolution scale and the adequacy of the fuel model approach. In fact a potential major draw back of the fuel model approach consists in the underestimation of the errors related to the fuel spatial variability with coarse spatial resolutions

[14] Pastor E., Zarate L., Planas E., Arnaldos J., 2003 – Mathematical models and calculation systems for the study of wildland fire behaviour. Progress in Energy and Combustion Science, 29: 139-153.

[15] Parsons R. A., 2006 - FUEL3-D: A spatially explicit fractal fuel distribution model. In: Andrews P. L., Butler W. (Eds.) – Fuels Management – How to mesure success. Conference Proceedings. 28-30 March 2006, Portland, OR: 253-272.

8 Final remarks

First, most of the concern with fire models has to do with spread rather than extinction. An indirect evidence that models do not capture some fundamental processes of the burning event is the difficulty to represent backfire actions and consequent fire extinction. A possible solution for this problem requires further investigation on the feedback process between fire and wind.

Second, as discussed in the previous paragraph, fuel description based on "fuel types" provides an average approximation of the spatial distribution of actual fuel loads and properties. However, the descriptions of fuel necessarily go together with the capability of the used fire models in order to have practical value. This issue requires a careful analysis of the proper spatial and temporal resolution to be used according to the model applications aims.

Third, the deterministic models, for which the simulation outcome is completely fixed for a given set of starting conditions, for probabilistic models the outcome will consist in a series of different possible fire scars, the shape of which is controlled by the input information.

Based on the obtained results, it would become possible to combine all the simulated fire scars into an 'average configuration' and to compute for each cell of the simulation grid a 'probability of burning' that is directly related to the number of simulated fire scars in which this specific pixel is burnt.

In any case, even in the use of probabilistic approach, the description of fuel will remain a critical issue. We suggest that further investigations should be addressed to define fuel properties related to the combustion process separately from the convection and related propagation processes.

9 An outline of the wind model integration work planned for the Fire Paradox simulation model

Context

The Fire Paradox board would like a document to give some insight into the work we plan to pursue as 'part two' of our contribution to the Paradox project. This note is intended to provide an outline.

Our approach

We want to make use of generally simple, fast wind flow modelling. This is our starting point, and we plan to extend this as necessary (and no further) to try to capture crucially important phenomena which are demonstrably significant to the overall model's performance. Instead of modelling everything and having the fire burn in that context, we'll work from the basics and try to apply additional adjustments only as necessary for the fire simulation.

WAsP Engineering

WAsP Engineering (WEng) does seem to offer what we need at first. It is fast, well-understood, accessible and capable within its well-known limitations. Given a wind observation wind, and a map of the topography, WEng will calculate a grid of predicted wind speeds and directions for various heights.

In comparison with other equivalent models it offers at least two clear advantages:

1. the surface aerodymanic roughness can vary over the modelled area. This means that fragmented landscapes including areas of open water can be more accurately represented
2. the input wind for the flow calculations can be synoptic/geostrophic. This means that you don't need to have a series of on-site wind observations coincident with the fire in order to generate a time series of wind conditions maps.

Limitations

Using a linear flow model like WEng means that we can expect poorer predictions in complex terrain. In particular, the zone of recirculation in the lee of a ridgetop may not be captured.

Some more advanced fire models are coupled: the atmosphere and the thermal/moisture balances are explicitly modelled, allowing the fire to have an effect on the wind environment in which it's burning. Our basic model does not support these interactions in any way.

Working around the limitations – complex terrain

For the problem of complex terrain, we will first explore the actual effect of wind model underperformance on the fire simulation, and then compare with more advanced, complex models which ought theoretically to produce a better result. The comparison will focus on the eventual fire model simulation prediction, rather than the intermediate wind model output. If we conclude that WEng is inadequate for our purpose (and that a better option exists), then we will either swap the model for something more complex, or will attempt to adjust the WEng output with some empirical or semi-emprical corrections if the effect does not need to be represented in detail.

Working around the limitations – thermal feedback

Coupled fire-atmosphere models do give rise to interesting and impressive output: with apparently convincing emergent fire behaviour. The cost is that they are complex and computationally demanding. A great deal of effort is expended to model the entire system, perhaps at the expense of detail which may be interesting or significant in itself. Our intention is to try to emulate the behaviour without explicitly modelling the atmosphere. The idea is that we are most interested in the fire front winds at only a few metres above ground level: we don't need information about the upper air for our purposes. All we want is to reflect the effect of the fire on the wind field, and this may be adequately captured by a thermally-driven adjustment to the background wind field: we're calling it 'implicit thermal convection.'

First, we use a linear flow model to predict the topographically-adjusted wind field (recalculated each time that the ambient wind conditions change), then for each iteration of the fire simulation model, we calculate a series of wind correction vectors at near-ground level, driven by the heat of the fire. The hotter grid cells would act as attractors: drawing air towards them and upwards. We don't care about modelling what happens to the air itself; just to capture the effect of these thermal currents on the wind field. Our aim is to add the correction vectors to the wind field vectors and then pass the resulting wind field into the fire contagion model.

Our first task would be simply to see whether this approach is feasible from its most basic implementation: each grid cell can be either burning or not-burning. Cumulative effects of neighbouring cells will be aggregated and balanced to produce the corrections within a limited radius. If this looks reasonable, then we would try to introduce effects proportional to the temperature of the fire in each location. We also imagine that a slope effect would be needed to draw more air in from downslope areas below a fire. When we have performed the most basic work to check that this is computationally feasible, we plan to use a mesoscale model to explore the magnitude of thermal effects on otherwise stationary air. We plan to try out different shapes of fire on different gradients and then try to use these values to drive our implicit thermal correction model.

In this way, we hope to pull together the best of both worlds: the simplicity and speed of a linear flow model, with the thermal effects calculated from a mesoscale model and introduced as more or less fixed fire model parameters.

We may be disappointed: this might prove to be ridiculous or inadequate for some reason. In that case we would need to decide whether to emulate the coupled modelling work from America (moving to some mesoscale model), or stick with producing a FARSITE equivalent landscape model in which thermal feedback effects are not captured.

Integration with the fire model

The fire simulation model will provide maps of orogaphy (elevation grids) and aerodynamic roughnesss (derived from vegetation). The input wind conditions are to be specified either as synoptic/geostrophic winds or as winds observed at some place in the modelled domain. The wind field will be calculated as necessary when any of the inputs change. This allows the possibility of allowing the fire to affect its own wind environment by changing the vegetation stucture as it burns.

The WEng output will consist of wind direction and speeds for various heights as needed, and possibly some extra information about the velocity derivatives and turbulence, if the fire simulation model is capable of making use of such inputs.

An intermediate layer will sit between the WEng wind model and the fire simulation, and we'll use this to apply corrections and adjustments which we feel are necessary to serve the particular requirements of the fire model. As explained above, these would include the implicit thermal correction, and perhaps some adjustments for known effects of complex terrain. We might also use this layer to introduce a diurnal (thermal) wind regime.

Workplan

Since our immediate task is investigative, we can't offer a complete end-to-end implementation plan.

The wind model part (working name 'Hirundo') and the fire simulation part (working name 'Tiger'), would also be expected to co-evolve: the developing requirements and capabilites of the one would affect those of the other.

On the wind modelling side, our first priority will be to construct a computational framework within which to explore this idea of implicit thermal convection. Then we'll probably do some test work at Risoe with a mesoscale model to try to generate reasonable parameters. This could be interfaced with an early, simple fire simulation model to see how well the interaction can work.

At this stage, we can investigate the effect of running a more advanced flow model and compare the fire simulation output in scenarios which we suspect will highlight differences (fire burning over a ridge top). If we need more than what WEng can offer, we'll have to consider switching to a CFD model.

If both of the above investigations indicate that we can proceed, we'll be able to try enhancements and tweaks to the implicit thermal convection approach, and perhaps introduce diurnal wind patterns.