Simulating fire ignition and initial propagation at road-forest interfaces

Thomas Curt [1], **Philippe Delcros** [2]

Abstract

Most points of ignitions are aggregated at the vicinity of roads in French Mediterranean Provence, but the flammability of vegetation and the probability of fire ignition and propagation to the neighbouring forests are poorly known. In this study we hypothesize that: (i) ignition at road-forest interfaces depends on the characteristics of vegetation facies including dead and live fuels; and (ii) the initial propagation also depends on the spatial patterning of the different components of the interface such as embankment or ditch. The aim of this paper is to simulate fire ignition and initial propagation in road-forest interfaces, to assess the relative importance of vegetation type, fuel treatment and spatial patterning of vegetation.

The cellular automaton simulator was implemented with different interface scenes (30x40 m), which describe vegetation patterns on the basis of field surveys. We studied three typical interfaces: (i) grass fields dominated by dicot grasses; (ii) grass fields dominated by graminae with scattered shrubs; and (iii) forest edges with mixed vegetation (graminae + litter + shrubs). We also simulated variants such as an increasing amount and a variable spatial pattern of shrubs, and the width of a low-flammable embankment made of dicot grasses and bare soil. The probability of ignition and propagation of each 20x20-cm cell were implemented on the basis of experimental data. For this purpose, we realized about 900 lab burning experiments combining five dominant vegetation types, two management practices, two modes of ignition, two wind speeds, and three levels of fuel moisture content). For each simulation run (10,000 replicates per run), we computed the probability for a fire to reach the neighbouring forest (P_{FR}). We also computed landscape metrics (e.g. connectivity indices) for each scenery, which are hypothesized to relate to fire propagation. Comparisons between sceneries were computed with analysis of variance.

Results indicate clear differences of fire propagation probability towards forest among the three interfaces studied. Dicots grasses and vegetation with low biomass reduce fire propagation, while mixed vegetation (grass + litter + shrubs) increase risk. The spatial patterning of vegetation is also a predominant variable to explain the probability of fire to reach forest. The lowest probabilities of fire propagation correspond to interfaces with decreasing gradient of vegetation flammability at the vicinity of forest. Low fuel moisture content increased significantly the probability of fire to reach forest. Partial validation of our results was operated using the BehavePlus software (modules 'Ignite' and 'Surface'). The perspectives after this study are to grade the main interfaces types according to their fire hazard level, and to help simulating firewise landscaping management practices to reduce fire risk at road-forest interfaces.

[1] *Cemagref – Mediterranean Ecosystems and Risks, 3275 route Cézanne - CS 40061 - 13182 Aix-en-Provence cedex 5, France; e-mail: thomas.curt@cemagref.fr*

[2] *Cemagref - Mountain Ecosystems, 2 rue de la Papeterie, BP 76, F-38402 Saint-Martin d'Hères cedex, France; e-mail : philippe.delcros@cemagref.fr*

Introduction

Most studies in southern Europe indicated that locations of ignition are aggregated at the vicinity of interface between wildland areas and human activities. About 50% of fire ignition are located at the edge of roads (including all road categories) (Prométhée) in connection with the high number of human-induced ignitions sources (Ref). These sources of ignition are varied: cigarettes (Alexandrian, 1995), road accidents, car exhausts, roadworks (mower or shrub-clearer engines, prescribed fires), power lines. They can produce variable modes of ignition: glowering (cigarettes), flaming (accidents, fires) or emission of sparks (power lines, engines, car exhausts) emitting variable energy, thus displaying differential ability to ignite vegetation.

However, differences in fire hazard ignition and propagation are poorly known because road-forests interfaces have specific features that may control fire ignition and initial propagation towards forests. First, dead fuels at interfaces between road networks and woodlands poorly known in terms of composition, annual growth cycle and moisture content, and flammability. Vegetation facies at interface have specific features such as the abundance of herbaceous species, mixings with dead wildland fuels including litter, twigs, leaves, and shrubs. Some species are sown or planted vegetation for recreational or management purpose. Literature on vegetation flammability and fire propagation at road-forest interfaces is quite scarce (Guijarro et al. 2001; Manzello et al. 2006).

Second, interface fuels are often modified by management practices for fire prevention, road traffic, or landscaping. In particular, grass-dominated fuels are periodically mowed and shrubs are cleared to limit fire initiation and propagation (Ref). These interfaces show specific structural components whose spatial patterning is hypothesized to affect fire ignition and propagation. These components can be embankments, ditches, slopes and forest edges. Fire behaviour and level of fire risk for adjacent forest are likely to vary according to the spatial patterning, dimensions, vegetation and fuel treatment of these components.

As a consequence, fire risk level and fuel flammability are hypothesized to be a combination of vegetation and fuel characteristics (composition, biomass, FMC, wind, slope and aspect, mowing and shrub-clearing), and interface structure. At this date, the fire hazard corresponding to different types of road-forest interfaces is not clearly stated. To simulate and model the level of fire risk of a forest adjacent to a road to be ignited by a fire, we built a cellular automaton (CA). Literature stated CA as powerful and simple tools to simulate a large number of fire propagations, with limited distortion from physical fire propagation models when used on small scales (e.g. Karafydillis & Thanailakis 1997; Berjak & Hearne 2002). Simulation is useful because postfire studies are limited and because experimentation is forbidden and undesirable in France during summer season. The simulator has been designed to test different realistic scenarios and variants, to examine the possible effects of spatial patterning or vegetation changes on ignition hazard. It will also be tested on theoretical sceneries, and at extreme conditions to test the accuracy and validity of the model. We used landscape metrics to assess the spatial pattern (e.g. connectivity) of vegetation within the interface, as fire spread is hypothesized to be controlled by these variables. We used flammability data stemming from experiments (ignition probability and 'sustainability') of small and undisturbed samples representative of the main vegetation facies at RNI. We used three submodels to simulate the location of the initial point of ignition within the scenery: (i) fully random location; (ii) location within the first-meter strip along the road; and (iii) location according to a decreasing exponential curve from the road. All simulations were conducted with low wind (3 km/h) and anhydrous vegetation, which correspond to frequent but not extreme conditions during summer.

In this paper we test the combined effects of vegetation (composition and possible management practices) and the interface patterning (internal spatial organization). Using extensive simulation runs, we tested the hypothesis that the probability of a fire ignited in the interface to reach the neighbouring forest (P_{FR}) is a combination of vegetation type, fuel moisture and spatial patterning of vegetation. On the basis of precedent consideration, we hypothesize that: (i) the influence of vegetation facies and fuel treatment should be visible through differences existing between interfaces having contrasted vegetation characteristics; and (ii) interfaces with similar vegetation characteristics but different spatial patterning should have different levels of fire risk of ignition and propagation towards forest. Our results will be partly validated by comparison with simulations using the BehavePlus software, and data from literature.

Materials and methods

Experimental data for vegetation flammability

Owing to the combination of vegetation facies and management practices, a large range of road-forest interfaces exists in the field. To select representative types, we investigated the variability of vegetation types on calcareous soils along road-forest interfaces (ca. 30 km), focusing on byways and state ways around Aix-en-Provence (southern France). This resulted in the selection of three major types of interfaces characterized by the predominance of specific vegetation facies (Table 1).

Vegetation sampling from April to October on the same sites (similar site conditions, similar vegetation facies). Half of the samples have been mown and shrub-cleared, while the other half was left intact. We collected undisturbed 18x20 cm vegetation samples. All samples were submitted to a standardized procedure for studying flammability. Vegetation samples were processed at different levels of moisture: fresh, air-dried (two days in a room), and oven-dried (two days in a ventilated oven at 60°C). For these simulations we used one ignition mode with a flaming cube and a low wind speed. We used a pine cube (1.9 x 1.9 x 1.0 cm) following the standardized procedure described by Guijarro et al. (2001). To obtain a flaming cube, it was ignited with the epiradiator then left out and rapidly put on the sample at a standard time of 45 seconds after ignition, still inflamed. Samples were burnt at a 'low' wind speed (ca. 3 km/h ~ 1 m/s). Wind was generated by a domestic fan and controlled by periodic measurements at the center of the sample with an anemometer (accuracy ± 0.1 km/h). To ensure repetability of our results, each batch (i.e., one vegetation type at one FMC value) was replicated 20 to 30 times. In total, we tested about 900 samples.

We assessed some variables describing ignitability and sustainability: (i) the time to ignition was measured as the time (in seconds) between the dropping of the cube at the centre of the sample and the eventual beginning of litter flaming. If a flame appeared within 3 minutes, it was considered as a positive test and classed as 'ignition'; (ii) the duration of flaming is the time with visible flames (in seconds). We noted the flame sustainability or the presence of smoldering; and (iii) the number of sides reached by fire (on the left, right, forward and backward directions). The probability of ignition P_i (i.e. ignition success) was computed as the ratio between the number of trials for one litter type and the number of successful ignitions (in %).

Ignition was considered successful when a flame appeared during the experiment and maintained during at least ten seconds. The probability of propagation P_p was computed as the ratio of the number of sides burnt to the four potential sides.

Building of interfaces scenes for simulation

We defined road-forest interfaces (RFI) are linear areas located at the border of roads and ending at the border of a forest. Each scenery representing an interface is composed of a border of a road which provides the ignition sources, the interface *sensu stricto*, and a linear forested border, wich corresponds to the 'target' that may be affected by fire. The interface can be made of different morphological components that have been described in the field: a ditch, an embankment, one or several successive parcels according to their predominant composition (herbaceous, litter, mixings). The presence and the size of these components can vary from a scenery to another. For simulation purpose, the road-forest interface depicts the landscape as a 40-meters long and 5- to 30-meters large area, depending on the real dimension in the field. Each scenery is composed of a grid in which each cell is 20x20 cm large to be coherent with the undisturbed vegetation samples that have been burned experimentally. The left side of each scenery is composed of cells adjacent to the road, and the opposite cells of the scene are composed of a continuous line of 'forest' cells.

The scenery dataset is composed of different complementary types of scenes, which are described in Table 1. Firstly, the three main representative types of interfaces. These sceneries are realistic since they are issued from precise field descriptions, with elementary cells of 20x20 cm. Secondly, we tested the impact of the spatial patterning of highly flammable vegetation patches representing a constant covering of 50% of the interface on P_{FR}. These clusters were made of vegetation mixings (graminae grass + pine litter + shrubs). For this purpose we computed different theoretical sceneries by modifying the pattern of these clusters among an interface made of dicot grasses. We compared a fully random pattern to an increasing pattern towards forest, and a decreasing one. Thirdly, we tested the effect of the width of a low flammable embankment made of 80% dicot grasses and 20% of bare soil, located at the border of the road. The width of the embankment varied from 0 to 5 meters.

Landscape metrics

We used different indices of landscape metrics to characterize the interface structure, i.e. the spatial patterning of the different vegetation (e.g. grass) and morphological (e.g. ditch) units. We focused on indices that are likely to represent the potential for a scene to propagate fire, such as indices of spatial connectivity. For this purpose, we used the FragStats 3.3 software ((McGarigal, 1994); McGarigal and Marks (1994). This allowed computing the indices of spatial patch cohesion, connectance, traversability, cohesion, contagion and adjacency. We also computed the contagion index proposed by He et al. (2000), which represents the degree of clumpiness of a landscape pattern.

Ignition hazard modelling with the cellular automaton

We built a cellular automaton (CA) to simulate fire ignition and fire spread as a diffuse or contagion process (Bevers et al. 2004). Actually, cellular automata are efficient and simple simulation tools to build probabilistic ignition hazard (Encinas et al. 2007). The behaviour of CA is believed to be self-organized criticality (Malamud et al. 1998). The CA model consists of a grid of cells, each of the cells being updated in discrete time steps according to a set of rules. The state of a cell at time *t* depends on the state of the *n*-nearest neighbouring cells at time *t*-1 or *t*.

For each gridded landscape scenery, we simulated the fire ignition hazard as the number of time when at least one 'forest' cell has been reached by fire for a large number of replicate simulations. To simulate the initial point of ignition, we used comparatively: (i) a random point located in the first-meter strip in contact with the road; (ii) a random point located anywhere within the scenery; and (iii) a point located at a variable distance from the edge of the road, according to an negative exponential curve predicting the distance of ignition sources at the vicinity of roads. This curve has been built by using data from literature (e.g. Berjak & Hearne 2002).

The simulator computes the ignition probability P_i for the first cell, which corresponds to the location of the initial firebrand. This ignition probability has been computed using the experimental data presented above. Once the first cell ignited (if it ignites), fire can spread to the eight neighbouring cells in function of their probability of propagation P_p measured experimentally. The process is repeated for each new cell ignited. Once burned, a cell becomes 'extinguished'. Thus, each cell can be unburned, burning or extinguished. For each simulation run, we replicated this process 10,000 times in order to take into account the stochastic dimension of the fire ignition and fire spread. At the end of the process, we estimate the probability of the forest to be reached by fire (P_{FR}) as the ratio between the number of times when at least one forest cell has been reached by fire to the number of simulation attempts.

Elements for validation

We used the BehavePlus v 3.0.1 (Andrews et al. 2004) software to simulate the probability of fire ignition from a firebrand (module 'Ignite'), then the 'Surface' module to simulate the surface fire spread. We especially computed the surface rate of spread (meters/min) and the maximal spread distance (meters). The implementation of fuel characteristics (e.g. one-hour fuel moisture) for the different fuel models was operated using our data from the field, and the customized fuel models proposed by BehavePlus for different types of grass, grass and shrubs, litter, and mixing made of litter, grass and shrubs. For the implementation of fuel moisture, we used the 16 fuel moisture scenarios proposed by BehavePlus, which cover a large range of moisture. We also used the dead and live fuel moisture scenario, implemented with the largest range of moisture that has been measured in the field. Simulations were operated at two wind speeds (3 and 10 50 km/h) corresponding to those experimented during the lab flammability experiments. Slope was set as null for all simulations. Air temperature was fixed at 25°C and fuel shading from the sun was set null for all simulations. Data from literature were also used to detect possible irrelevant results. Advice from experts of fire behaviour was also requested to discuss the results.

Results

Simulation based on actual scenes

Our results indicate clear differences in the probability of the neighbouring forest to be reached by fire among the three representative interfaces (Figure 1). Interfaces dominated by dicots grasses ('prairie') that are weakly flammable represent a low level of risk of fire propagation towards forest, although they contain clusters made of flammable mixings of graminae, pine litter and shrubs. The P_{FR} values decreased with the distance from the road, but clearly increased at lower fuel moisture contents. Interfaces dominated by graminae grasses ('restanque') had slightly higher P_{FR} values for the fresh and air-dried modalities, but much higher values for the oven-dried modality. Interfaces dominated by grass-litter-shrub mixings ('forest edges') have a much higher ignition and propagation probability than the others. They were clearly the most risky and favourable to fire propagation: P_{FR} ranged from 60 to 100% whatever the FMC value and the width of the interface when the initial ignition points were distributed randomly or according to a negative exponential. P_{FR} values were low only for low FMC values and when the initial point of ignition was located within the first-meter strip near the road.

The risk level varied logically with the FMC in all interfaces, with increasing P_{FR} as FMC decreases (Figure 1). It is noteworthy that P_{FR} is high for all interfaces for the oven-dried FMC modality, which corresponds to values measured in the field during the driest period of summer.

The location of the initial ignition point within the interface has an effect on P_{FR} (Figure 1). In general, P_{FR} values are maximal when this point is randomly distributed among the interface. They are lower when the initial point is located according to a negative exponential curve function of the distance from the road. When the initial point is located within the first-meter strip beside the road, values are low to null. This one-meter strip, which is composed of weakly flammable vegetation and of 20% of non-flammable bare soil, can decrease P_{FR} from 5 to 10 times in highly flammable interfaces.

The P_{FR} values for the 'restanque' and the 'prairie' interfaces decrease when the width of the interface increases, that is to say when the distance from the road to the forest increases (Figure 1). The vegetation of these two interfaces has low or medium P_i and P_p values. In contrast, there is no effect of the interface width for the 'forest edge' sceneries, which is characterized by vegetation mixing with high P_i and P_p values.

Simulation of management options and landscape patterns

The spatial patterning of highly flammable clusters made of a graminae-litter-shrub mixing clearly affected the risk of forest to be reached by a fire generated within the interface. This is true for fresh and air-dried vegetation, but not for the oven-dried modality. In comparison to the random distribution, the P_{FR} values were enhanced when the percentage of flammable clusters increased towards forest. They clearly decreased when this gradient was decreasing towards forest (Figure 2).

Likewise, the presence and the width of an embankment made of low-flammable vegetation and bare soil can reduce P_{FR} in the three main interface types (Figure 3). For vegetation at low fuel moisture ('fresh') the fire risk is reduced is a very low level whatever the interface. It remains high for the 'restanque' and 'forest edge' interfaces when simulating P_{FR} for oven-dried vegetation.

Discussion

Differences in risk level among types of interfaces

The three main interfaces types used in this paper have clear differences of risk level, which result from differences in vegetation composition but also in the spatial organization of the interface. Simulation results are logically affected by the P_i and P_p values affected to each modality combining a vegetation facies and a fuel moisture content.

But the results were also affected by the location of the initial ignition point. Location at the immediate vicinity of the road (1-m strip) is hypothesized to mimic ignitions generated by cars or maintenance workers. This can reduce strongly the probability of a fire to reach the forest since a fire-resistant strip of few meters can limit fire initiation and propagation. This confirms that fire-preventing management practices such as grass mowing and/or shrub-clearing can be efficient (Alexandrian 1995), depending on their intensity, seasonality and repetition along the summer season. Grass mowing without removal can enhance fire ignition during summer period owing to the presence of dead (i.e., anhydrous) grass remnants. Conversely, grass mowing can limit drastically fire spread during dry summer spells. Location of the initial point of ignition according to a negative exponential function corresponds to a ballistic drop of a light mode of ignition such as a cigarette butt. In this case, differences among interfaces almost mainly depend on the distance between road and the forest or wildland. For such interfaces, the most efficient way to limit fire propagation to forest could be an extensive fuel treatment strip of several meters at the vicinity of the forest. Random location is hypothesized to mimic walkers or land managers that can ignite a fire anywhere within the interface. This type of ignition results in low differences between the different types of interfaces since it can be very close to the forest.

Elements for validation

Direct and complete validation is impossible since experimental fires are not authorized at these interfaces, especially during the fire peak season in summer. However, elements of validation of some of our results can be obtained from simulations using the BehavePlus software. Behave indicates probabilities of ignition depending on the fuel moisture scenario, ranging from 22 to 88%. This is coherent with our results. Surface rate of spread can be low for some fuels with low load, even with variable fuel moisture scenarios. The BehavePlus simulations also indicate that some fuel types encountered at road-forest interface or similar types from Behave have maximal surface spread distance lower than 30 meters. In particular, short grass or grasses with low to moderate load have maximal surface spread distance lower than 30 meters, or even lower than 10 meters for the 'fresh' moisture scenario. Likewise, spread distance is lower than 10 meters for compact pine litters and shrubs with a low fuel load. Mixings made of grass and shrub, even added with litter, have higher spread distance. These data confirm our simulations results, with low- to null P_{FR} values for interfaces made of fresh dicots grasses and compact litters.

Interest and limitation of fire simulation for management

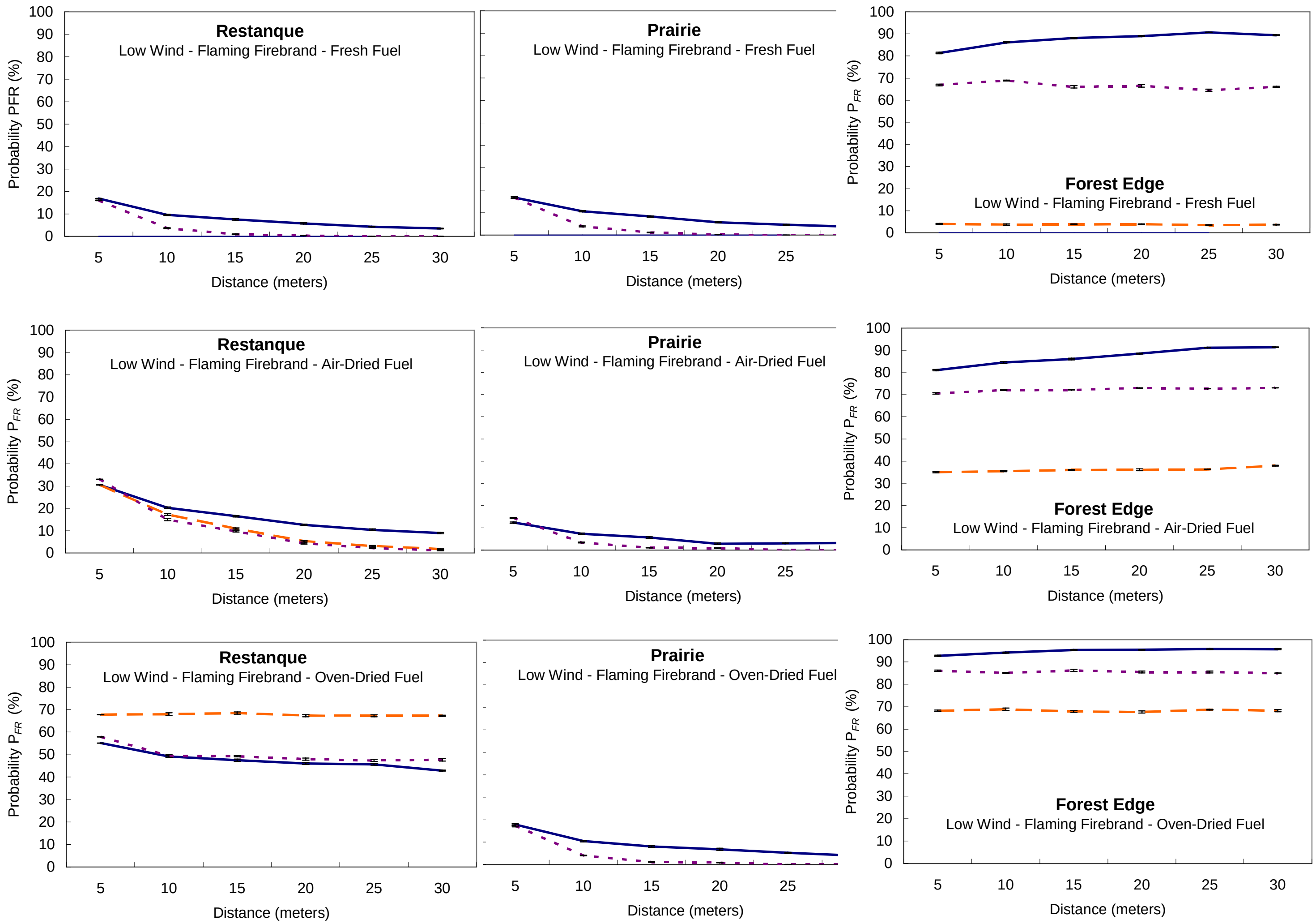
The use of a cellular automaton to simulate fire propagation throughout road-forest interfaces is useful since it only requires experimental data. It is especially adapted to simulate low-intensity fire propagation on short distance. The main interest is to get rapid and reproducible results for a large set of interfaces. However, it remains difficult to assess to which extent our simulation results differ from those stemming from physical or empirical fire propagation models (e.g. Farsite). All CA are very sensible to the values implemented in each cell, which condition the fire ignition and propagation towards neighbouring cells. A sensibility analysis could be carried out to assess to which extent a small change in P_i and P_p values for each vegetation facies and external conditions (wind and FMC) could change the result of simulations. Likewise, CA are sensible to the density of cells having high probability of propagation. Literature indicates that a theoretical percolation threshold (p_c) exists, which corresponds to about 0.59 (Beer 1990). Above this value, fire propagation to the whole scene is likely.

The main perspective of this study is to grade and to map the probability of fire towards forest for the largest range of interfaces, and for various conditions of wind, modes of ignition and fuel moisture. Road-forest interfaces cover a large surface but resources for treating them are limited. The spatially explicit modelling approach is a valuable tool for identifying fuel treatment and their location in the landscape, in terms of effectiveness for reducing wildfire risk and protecting forest from fires. Firewise landscaping techniques such as greenstripping could be applied to these interfaces (e.g. Loehle 2004; Bevers et al. 2004).

Table 1—*Characteristics of the three main interface types studied.*
Interfaces are 40x30 meters large. The landscape metrics refer to the FragStat™ software [(a)] and to He et al. (2000) [(b)]

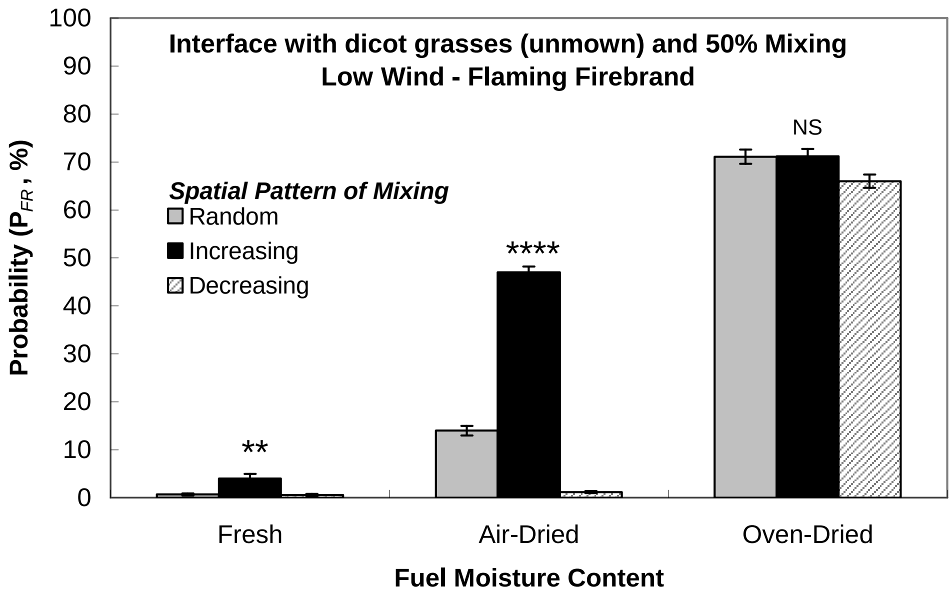
Type of interface	'Prairie'	'Restanque'	'Forest Edge'
Vegetation	Dicot grasses (80%), graminae grasses (10%), pine litter (5%), shrubs (5%)	Dicot grasses (10%), graminae grasses (60%), pine litter (10%), shrubs (20%)	Graminae grasses (60%), pine litter (20%), shrubs (20%)
Landscape Metrics			
Contiguity Index [(a)]	0.10	0.29	0.24
Contagion Index [(a)]	92.9	92.5	88.5
Interspersion/Juxtaposition [(a)]	46.0	12.1	6.7
Cohesion Index [(a)]	99.5	99.0	98.9
Shannon Index [(a)]	0.32	0.64	0.48
Aggregation Index [(b)]	98.9	91.7	84.5

Figure 1—Comparison of the probability of the neighbouring forest to be reached by a fire initiated within the interface for the three main interface types, three levels of moisture content and for an increasing distance of the interface. The three lines correspond to the location of the first point of ignition. Continuous blue line: Fully random; Purple dotted line: negative exponential; Orange dotted line: random within a 1-m strip near the road



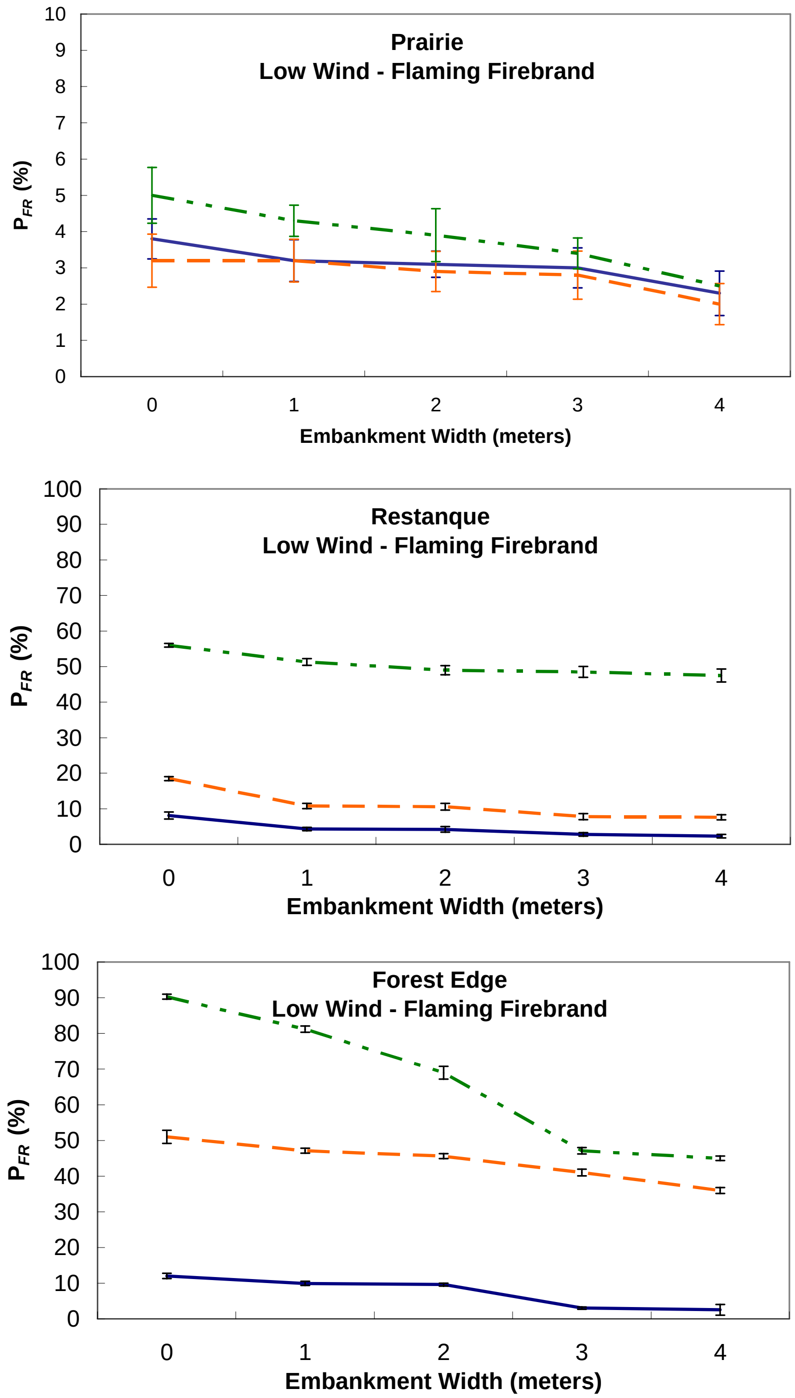
[1] *Cemagref – Mediterranean Ecosystems and Risks, 3275 route Cézanne - CS 40061 - 13182 Aix-en-Provence cedex 5, France; e-mail: thomas.curt@cemagref.fr*
[2] *Cemagref - Mountain Ecosystems, 2 rue de la Papeterie, BP 76, F-38402 Saint-Martin d'Hères cedex, France; e-mail : philippe.delcros@cemagref.fr*

Figure 2—Effect of the spatial patterning of a highly flammable 50% mixing on the probability of forest to be reached by fire for an interface with unmown dicot grasses. Large vertical bars are mean values, and small lines are standard errors (10,000 simulations per run). For a same level of fuel moisture, the statistical test indicates significant differences among modalities of spatial pattern (NS= non significant; ** p<0.01; **** p<0.0001)



[1] *Cemagref – Mediterranean Ecosystems and Risks, 3275 route Cézanne - CS 40061 - 13182 Aix-en-Provence cedex 5, France; e-mail: thomas.curt@cemagref.fr*
[2] *Cemagref - Mountain Ecosystems, 2 rue de la Papeterie, BP 76, F-38402 Saint-Martin d'Hères cedex, France; e-mail : philippe.delcros@cemagref.fr*

Figure 3—Effect of the width of a low-flammable embankment (80% dicot grasses and 20% bare soil) on the probability of forest to be reached by fire for the three main types of interface and for the three levels of fuel moisture. Continuous blue lines: fresh vegetation; orange broken lines: air-dried vegetation; green dotted line: oven-dried vegetation. Vertical bars are confidence intervals (LSD procedure, 95%)



References

Alexandrian, D. (1995) Interventions anti-incendie nécessaires sur la section courante des autoroutes. *Options Médit.*, 25, 121-131.

Andrews, PL, Bevins, CD, Seli, RC (2004). BehavePlus fire modeling system, version 3.0: User's Guide. Gen. Tech. Rep. RMRS-GTR-106WWW. Ogden, UT: Dept. of Agriculture, Forest Service, Rocky Mountain Research Station. 132p.

Beer, T (1990). Percolation theory and fire spread. Combustion Sci. Technol. 72: 297-304.

Berjak, SG, Hearne, JW (2002). An improved cellular automaton model for simulationg fire in a spatially heterogeneous Savanna ecosystem. Ecological Modelling 148: 133-151.

Bevers, M, Omi, PN, Hof, J (2004). Random location of fuel treatments in wildland community interfaces: a percolation approach. Can. J. Forest Res. 34: 164-173.

FragStats v. 3.3. Spatial Pattern Analysis Program for Categorical Maps. Dep. Natural Resources Conservation, Univ. Massachussets, Amherst, MA 01003, USA (http://www.umass.edu/landeco/research/fragstats/fragstats.html).

Guijarro, M., Hernando, C, Diez, C, Martinez, E, Madrigal, J, Lampin-Cabaret, C, Blanc, L, Colin, PY, Pérez-Gorostiaga, P, Vega, JA, Fonturbel, MT (2002) Flammability of some fuel beds common in the South-European ecosystems. Forest Fire Research & Wildland Fire Safety, Viegas (ed.), Millpress, Rotterdam.

He, HS, DeZonia, BE, Mladenoff, DJ (2000). An aggregation index (AI) to quantify spatial patterns of landscapes. Landscape Ecology 15: 591-601.

Karafydillis, I, Thanailakis, A (1997). A model for predicting forest fire spreading using cellular automata. Ecological Modelling 99: 87-97.

Loehle, C (2004). Applying landscape principles to fire hazard reduction. Forest Ecology Management 198: 261-267.

McGarigal, K., Marks, BJ (1994) Spatial pattern analysis program for quantifying landscape structure. FRAGSTATS v. 2.0. *Forest Science Department, Oregon Stat Univ., Corvallis, OR, USA.*

McGarigal, K., S. A. Cushman, M. C. Neel, and E. Ene (2002). FRAGSTATS: Spatial Pattern Analysis Program for Categorical Maps. Computer software program produced by the authors at the University of Massachusetts, Amherst.

Prométhée La banque de données sur les incendies de forêts en région Méditerranéenne en France. *http://www.promethee.com/*.