Modelling fuel distribution with cellular-automata for fuel-break assessment

COHEN, Mathilde & RIGOLOT, Eric
Institut National de la Recherche Agronomique, Unité de Recherches Forestières Méditerranéennes, Avenue A. Vivaldi, 84000 Avignon, France. Phone : (+33) 4 90 13 59 55 – Fax : (+33) 4 90 13 59 59 - E-mail: cohen@avignon.inra.fr ; rigolot@avignon.inra.fr

ETIENNE, Michel
Institut National de la Recherche Agronomique, Unité d'Ecodéveloppement, Domaine St Paul, Site Agroparc 84914 Avignon cedex 9, France. Phone : (+33) 4 32 72 25 77 – Fax : (+33) 4 32 72 25 62 – E-mail: etienne@avignon.inra.fr

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ABSTRACT: Complete physical models are being developed and they are currently used to assess the effectiveness of fuel-breaks at the local scale. In order to build up robust inputs for such a model, a fuel distribution model has been developed with cellular-automata. It is based on a field description of belt-transects perpendicular to the main fuel-break direction, by means of dominant species cover, height and aggregation, assessed on 25 m x 25 m elementary squares. Among the four vegetation types (tree, shrub, herb, litter), several classes of layers were distinguished.

The current requirements of the physical model are 2D (x, z) data, distributed on a 25 cm x 25 cm grid. Each cell of the grid must be informed with physical and chemical data for each fuel family. The developed model was designed to provide the fuel family repartition among the grid. The cellular-automata first simulated the location of the upper left hand corner of the clumps of each species according to their cover and aggregation. Then the arrangement of the different layers of vegetation was calculated according to the height, the distance between trees and shrubs, and specific rules of exclusion based on incompatibility between species (e.g. no shrub below any holm oak) or direct relationships between layers (e.g. there is always litter below tree canopy). The shape of each clump and fuel family distribution among the cells of the clump were designed according to the current knowledge on species architecture.

Several simulations based on the same set of field data were compared in order to assess the variability of the outputs of the model and to validate the vegetation representation according to the observed vegetation. The model was tested on contrasting woodland and shrubland stands under different fuel-break configurations. This coupling between fuel and fire behaviour modelling is a promissory approach to test management rules to improve fire prevention efficiency.

1 INTRODUCTION

The use of fuel-breaks in Mediterranean regions, Australia or in the United States is a key point of wildland fire prevention (Agee et al., 2000). These breaks correspond to areas where the amount of fuel is reduced and are designed to locally alter fire behaviour and therefore to limit damages and impacts to people and goods, to reduce the area of the forest burnt and may also prevent fire ignition. Up until now, most of the fuel-breaks were designed according to an empirical knowledge about the way fire should behave in such areas. We may consider the fact that land managers or study offices still lack operational tools or methods either to create new fuel-breaks or even to evaluate the effectiveness of existing ones.

Given this context, several methods have been developed for a couple of years to provide scientific justifications in the assessment of fuel-breaks. In this domain, experimental fires (Wilson, 1988) can be worthwhile but they may not always be easy to implement especially in highly urbanised regions. Some others methods, based on expertise, lead to an expert appraisement approach (Rigolot, 2002) or to the use of feed-back experiences on previous wildland fire (Lambert & al, 1999) to evaluate already existing fuel-breaks. On the other hand, progresses made in the field of fire simulations offer also great hope: new modelling tools can help to understand fire behaviour. However, most of these fire-behaviour models are supposed to run at a large scale such as BEHAVE (Rothermel, 1983) or FARSITE (Finney, 1998). Fuel models, which are coupled with these physical models, were developed to fit with a landscape scale, so they are all based on standards supposed to account correctly for large portions of forest, sometimes even using remote-sensing data (Lagarde, 1994). But this approach is unsatisfactory to study the local impact of fuel-breaks on fire behaviour. Moreover, besides being used for large scale, fuel models were also designed for rather continuous and uniform fuel bed (Burgan & Rothermel, 1984). And yet, vegetation found on fuel-breaks tends to be rather heterogeneous as long as bush clearance and tree cutting are regularly done. Vertical and horizontal discontinuities in fuel are a goal wanted by land managers in order to weaken fire dynamics. Even if some improvements were made in this respect, to estimate fuel characteristics in a chaparral (Conard & Regelbrugge, 1993) or to produce tables or guides, based on statistical relationships (Sneeuwjagt & Peet, 1985 ; Fernandes & al, 2000), little is known on how to take into account variations in spatial distribution of fuel vegetation.

For all these reasons, we developed a fuel distribution model that could be used in a physical fire-behaviour model applied at the scale of a fuel-break (around 100 meters) and which would not overbook specificity of Mediterranean wildlands and fuel breaks. The physical model is based on a multiphase approach which consists in solving conservation equations (mass, momentum, energy) (Morvan & Dupuy, 2001 ; 2002). In this approach, vegetation is described by several fuel families. A fuel family represents all the solid particles of vegetation which have the same properties concerning physical and chemical processes involved in a wildland fire. We distinguished here several kinds : needles, leaves, grass, twigs, and branches… In addition to that, this model is currently running in 2 dimensions (x, z) (the x axis representing the direction of fire propagation), which we had to take into account in our fuel model.

So, the main question was how can we describe and model fuel distribution at a fuel-break scale? And how a 3-D vegetation structure could be transformed into the 2-D localised structure, imposed by the physical model ? This paper explains our methodology to provide robust inputs for the fire behaviour model, discusses the preliminary results and proposes potential outputs of this work. These researches were partly led in the frame of a European project, Fire Star, which aims at producing a decision making system for forest fire prevention in wildland-urban interfaces in Mediterranean regions.

2 A NEW METHODOLOGY TO MODEL FUEL AT A STAND SCALE

2.1 *The use of a cellular automata as a tool to model fuel distribution*

The idea was to build up on the whole width of a fuel-break, a vegetation vertical profile (x, z) based on descriptive data collected on elementary field squares. We wanted to find a compromise between time-consuming field measurements and a satisfactory average representation of the fuel-break vegetation profile. In this perspective, cellular automata seemed to constitute a perfectly adapted tool. Cellular-automata have been widely used for the last decade in several domains such as natural resources management, economic and social sciences, often in association with multi-agent systems (Bousquet & al, 1999). A cellular automata is constituted by a matrix, a grid of cells that can be influenced by their neighbors state and can be gathered into aggregates with specific properties. They are thus usually used to study spatial impacts, and was already used in the wildfire domain to reveal relationships between fire and heterogeneity of fuel, but at a landscape scale (Hargrove & al, 2000).

The modelling work developed an automatic procedure to perform a randomised transformation of non localised data from experimental plots into a spatial grid made of the 25 cm x 25 cm elementary cells required by the fire behaviour model. We used the CORMAS simulation platform (Bousquet & al, 1998), and the procedure was coded with the object-oriented language Small-Talk under the VisualWork© environment.

Each grid built up by the cellular-automata covered a 25 m long and 15 m high profile, that is to say a 62 x 100 grid of 25 cm x 25 cm cells. The last 2 lines at the bottom of the grid were devoted to the litter layer and the herbaceous layer and are the only ones that do not represent real height.

In the following paragraphs, we will present the 4 steps leading to the final outputs of the fuel distribution model.

2.2 *First step : collecting fuel data in the field*

The field description used here was quite similar to approaches used in the cartography of vegetation (Etienne & Rigolot, 2001). It aims to give an average representation of the fuel distribution. It was made thanks to a transect constituted of several 25 m x 25 m elementary squares marked on the soil by stakes, and placed perpendicular to the main fuel-break direction. At least one square had to be localised in the original wildland stand, as control and all the other squares were placed along the depth of the fuel-break. It takes approximately less than 1 hour to make measurements on one square.

Vegetation was described according to vegetation types and stratums. We distinguished 4 vegetation types : tree (ligneous species higher than 2 m), shrub (ligneous species below 2 m), herbs, and litter. Litter included needles or dry leaves, twigs or branches, and dry herbaceous lying on the ground. Among the 4 vegetation types, 8 classes of stratums were defined, according to height (Table1). On each elementary square and for each stratum, several parameters were measured.

Litter cover was estimated according to 3 classes (0 to 50%, 50 to 75%, more than 75%). If cover was greater than 75%, then litter thickness (in cm) had to be measured (Rigolot & al, 1996). These measurements were repeated 30 times over a small 50 cm x 50 cm square, at every one meter (about one step) on the diagonal line of the elementary square. Global composition of litter was also noted.

As far as herbs are concerned, cover (with the real percentage), aggregation and height were estimated for all species together, without distinction. Aggregation was evaluated thanks to the Folk's diagram (Folk, 1951) : it represents the way saplings are distributed within the elementary square and was assessed by 4 letters defining 4 classes. The letter "A" meant that species were gathered in one spot and that aggregation is maximum. On the contrary the letter "D" was used when a species was scattered and its fragmentation maximum.

Table 1 : correspondence between the 4 vegetation types and the 8 stratums

Height (m)	*stratum*	*litter*	*herbs*	*shrubs*	*trees*
16 - 32	8				x
8 - 16	7				x
4 - 8	6				x
2 - 4	5				x
1 - 2	4			x	
0.50 - 1	3			x	
0.25 – 0.50	2			x	
0 – 0.25	1			x	
-	0	x	x		

In each stratum which belongs to shrubs or trees, cover and aggregation of the 3 most dominant species encountered, and whose cover is greater than 10%, were estimated. These measurements had also to be made for the whole stratum, all species together. For trees, data were completed by estimates of average height of the lower (first green leaf or needle) and higher level of tree foliage. Information about the way stratum were globally distributed among the square were added.

Lastly, cover of rocks and area of infrastructure (ex. a road) were recorded in each square.

All these non destructive field measurements were used (table 2) in the fuel distribution model which runs thanks to the cellular-automata.

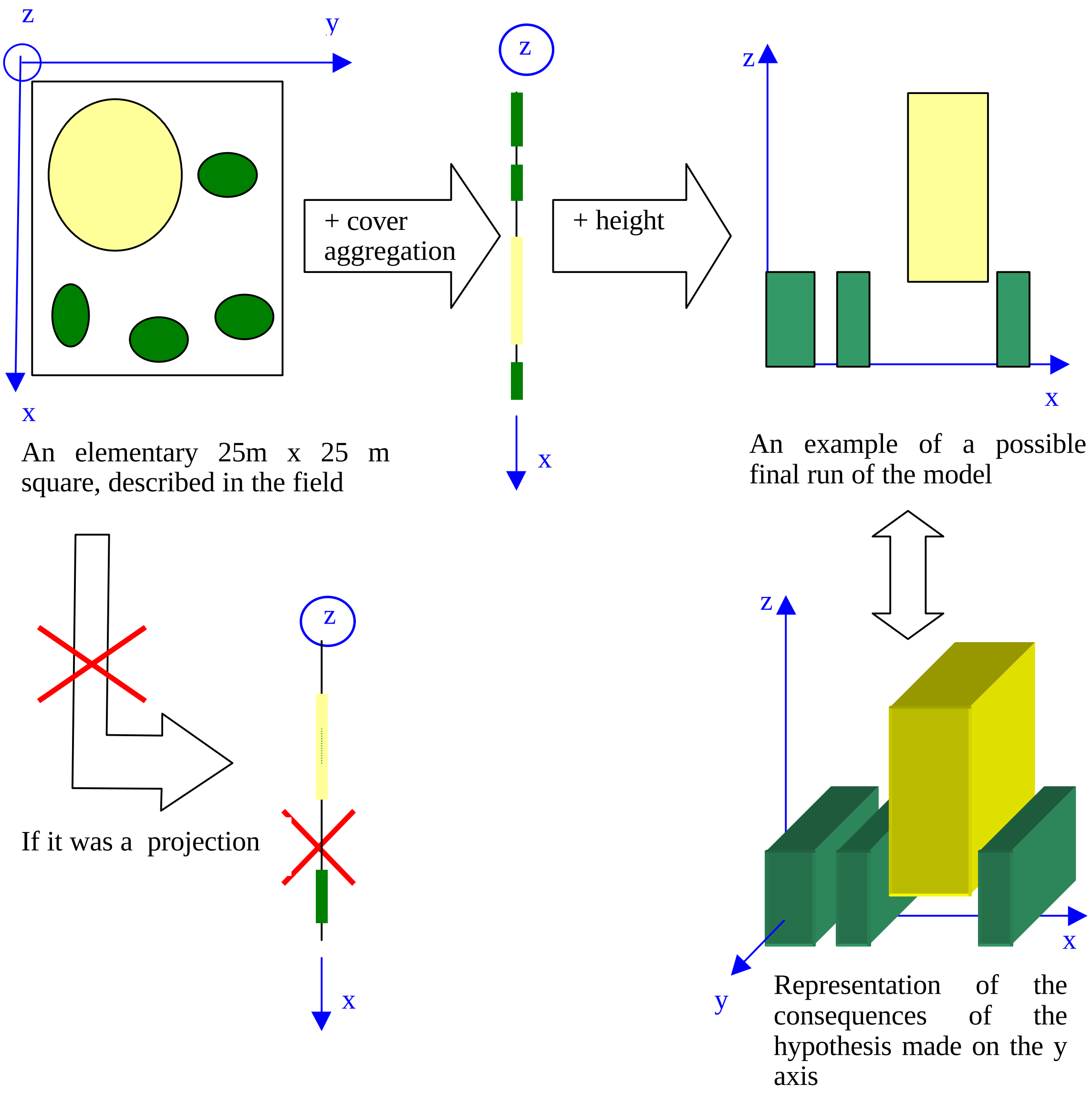
Table 2 : example of a file used as input for vegetation data in the cellular automata for trees, shrubs and herbs.

Species	Stratum	Cover (%)	Aggregation	Height -min (cm)-	Height -max (cm)-
Pinus halepensis	7	10	A	500	1250
Pinus halepensis	6	5	B	200	850
Quercus ilex	6	10	C	150	600
Quercus ilex	5	20	D	0	350
Quercus coccifera	4	13	D	0	0
Quercus coccifera	2	13	C	0	0
Quercus ilex	1	38	C	0	0
Herbs	0	38	C	0	20

2.3 *Second step : implementing rules in the cellular-automata to transform non localised data into a 2-D (x, z) grid through an automatic procedure*

The transformation to get from the (x, y, z) field description to a (x, z) plan, corresponds to a run of the average image of the structure and the composition of the vegetation from the field data. This run represents one possible event among all those that are defined by general distribution constraints implemented in the model and is not a classical projection (Fig. 1). Distribution rules to construct the runs were deduced from the 3 criteria measured on the field.

Cover and aggregation were used to generate and localise each shrub or tree on the x axis (in the fire propagation direction) and to define their width. Namely, all the covers collected on field were totally reproduced on the profile. Once the number of clumps of a species in one stratum had been calculated thanks to the aggregation mark, it was possible to define an average width for clumps, taking into account each cover. For instance, for a maximum aggregation the cellular-automata will represent only one clump, which will have a width equalling its cover. In an other situation, when aggregation is very low, there will be around 5 clumps whose width will be approximately the number of clumps in one species divided by its cover. In fact, some variability in the distance between each clump and in width of each clump was added. But a minimum width of tree canopy was defined to avoid unrealistic representation. Once each clump was localised, heights measurements were used to define the maximum and minimum height of individual crown within a stratum on the z axis. Thus, trees and shrubs are represented only thanks to their crown. It was no worth taking into account trunks because they are not significantly involved into fire propagation.



An elementary 25m x 25 m square, described in the field

An example of a possible final run of the model

If it was a projection

Representation of the consequences of the hypothesis made on the y axis

Figure 1. Diagram describing how the transformation was made, to transform the field description into the 2D plan using first, cover and aggregation, then height. The red cross underlines a counter example of what is not done. Each colour represents a species represented by a square, a circle or a line depending on view chosen.

Other rules had to be added to account for biological and ecological behaviour of each species in its ecosystem. In this respect, rules of exclusion of species were implemented based on incompatibility between species. For example, individual knowledge or expertise about Quercus ilex (holm oak) behaviour in Mediterranean wildland led us to exclude the possibility to have some shrubs below a clump of Quercus ilex. We also used direct relationships existing between layers : it is a well known fact that litter is mainly found below ligneous species. So, in the model, cells with the biggest amount of litter were distributed in priority below zones where trees or shrubs are overlapping.

2.4 *Third Step : improving specific architecture on tree and shrub crown*

In addition to the data collected previously to implement some rules and constraints in the fuel distribution model, some other data are meant to improve some allometric relationships to evaluate tree growth and architecture (Porté & al, 2000). The criteria were :

- tree foliage extension,
- diameter at breast height (DBH) of every single tree of each elementary square,
- age of trees on the whole transect,
- average distance between tree crowns (or trunk).

The relationships were used to improve the average shape of each clump in the cellular automata. Great attention was put on characteristics of tree growth on fuel-breaks which may behave in a different way from trees in a “normal” situation in forest.

We also had to fill in these shapes in order to know what kind of fuel family is found in each cell (needles or leaves, twigs, branches, empty space, etc …). Information is given by the plant architecture method (Barczi, & al, 1997) developed by our partners in Cirad, Montpellier (France). It aims at simulating architecture of plant by characterising growth and ramification and knowing its edification mechanism. Many typical Mediterranean plants (*Pinus halepensis, Quercus ilex, Q. coccifera, Cistus albidus, Rosmarinus officinalis, …*) have already been described that way and are thus available in “a catalogue” (Caraglio & al., 1996). The fuel family distribution among the cells of each clump can then be deduced and designed according to the current knowledge on every species architecture.

2.5 *Fourth step : taking into account fuel families to constitute the final data needed by the fire behavior model*

To provide inputs for the physical model, each cell of the grid must also be characterized by the ratio of each fuel family, and by the following physical parameters defined for each fuel family.

Destructive field and laboratory measurements give accurate data on fuel for the fire propagation model. In the Mediterranean region, we can count on previous studies that already offer a list of several species that have been precisely described in terms of physical and chemical parameters (Bardadji, 1996). In fact, the following data (volume fraction, particle shape and size, length, surface to volume ratio, moisture content, density of the particle) describing a fuel-family are supposed to be inputs of the fire propagation model. So, if all data are not available, classical laboratory measurements on new species will have to be made before being able to use outputs of the cellular-automata. All these data will fill in a data base about characteristics of Mediterranean species.

Thanks to the fuel family distribution in each cell, the grid can then be finally refined with all the parameters for numerical calculation purposes.

3 PRELIMINARY RESULTS AND DISCUSSION

3.1 *Results of simulations*

Each run of the fuel distribution model corresponds to one event among all the possibilities defined by the set of rules created in the model.

Several simulations based on the same set of field data are currently made in order to assess the variability of the outputs of the model and to validate the vegetation representation according to the observed vegetation. At present, we can already point out the fact that the method is stable and reliable for a high cover of tree strata whereas in case of low tree cover, the random bias affects strongly the trees location. Actually, in the first situation (Fig. 2), several runs of the cellular-automata give very similar results : the variability of each clump of holm oak (*Quercus ilex*, green rectangles) is well represented as well as the effect of pruning seen by the lower line of leaves. Litter of these trees is placed under each clump.

The figure 3 shows the automatic transcription of a square described in an Alepo pine (*Pinus halepensis* in red) and holm oak stand. In this case, the variability between each simulation is due to the fact that the first cell designing the beginning of a tree is taken randomly from a set of cells which gets bigger as cover decreases.

The Fire Star project will give the opportunity to test this fuel distribution model with various Mediterranean ecosystems, ranging from garrigues to maquis, from mixed pine and oak stands to pure coppice and then improve step by step the accuracy of the model.

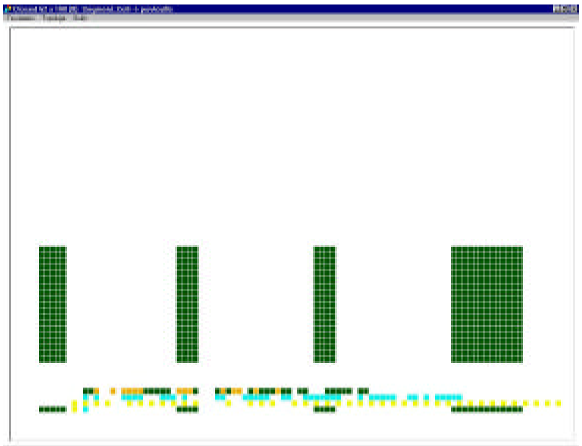


Figure 2. Representation with the cellular automata of a 6 m Quercus ilex stand with 45% of cover.

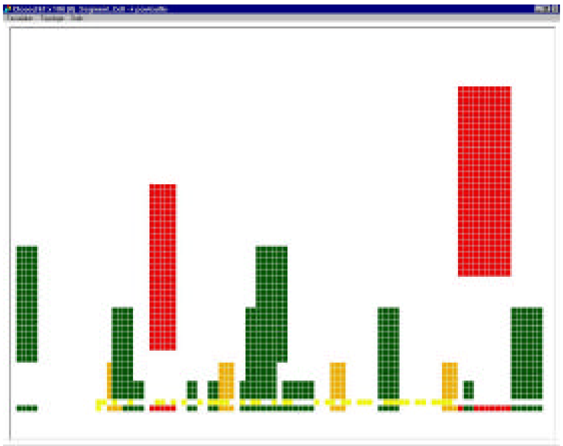


Figure 3. Representation with the cellular automata of mixed pine and oak stand with less than 15 % cover.

3.2 *Discussion*

The use of cells of 25 cm x 25 cm comes from a compromise between, on the one hand, the actual performances of numerical calculations, the precision accepted for the shape of vegetation or in destructive measurements, and on the other hand, the precision expected for the results. It revealed to be adapted to our use. The grid has also presented the advantage to give a description of fuel and some information at the level of the particle which is much more precise than other fuel models. Yet, the fact that 2 layers (herbs and litter) are individualised in 2 lines produces a configuration which is relatively different from reality. It is not totally satisfying in situations where herbs and shrubs are mixed, as it is the case with *Brachypodium ramosum* and *Quercus coccifera :* in the model, we will suppose that they are in 2 separated strata.

But all the more, it can not be denied that a 2 dimension model is necessarily limited to certain types of situations where the fire line will maintain a rectilinear shape (one direction of wind, large homogeneous layers of vegetation). The major hypothesis made on vegetation (uniform on the y axis) is then not valid anymore when it is made of many clumps scattered with a wind with a relatively changing direction. Even if most of the Mediterranean fuel breaks are often treated homogeneously by foresters (to sparse time), it will be an enrichment to be able to study some more specific situations, with sparse clumps of trees and shrubs. So, in the short run, the physical model will be implemented in 3 dimensions. In this case, and even if the cellular automata was partly used because of the 2D constraint, we will keep this tool anyway to avoid loosing time in making spatialised measurements on the field, and as it revealed to be particularly appropriate to these kind of problems.

Finally, we were assuming that the 3 field criteria (cover, aggregation and height) were sufficient enough to represent the main variability of fuel vegetation confronted to the point of view of the fire and thus to account for heterogeneity. We will continue to check this hypothesis but if it was the case, these criteria will constitute useful indicators as phyto-volume can be deduced from them, for example. They could thus be used to give managers prescriptions and rules to design efficient fuel-breaks.

4 CONCLUSION AND PERSPECTIVES

We developed a new way to model fuel distribution at the fuel-break scale by using a cellular automata, in order to take into account more accurately specificities of fuel-breaks. This method is currently used, coupled with a physical model, in the European project Fire Star to assess Mediterranean interfaces. But, it can be apply to any other type of fuel-breaks or ecosystems. It aims in the long run at developing a decision making system that will help land-managers to elaborate fuel-breaks or interfaces. In the French context of forest fire risk prevention plans it will be useful to enhance the quality of fire prevention.

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