Pinus halepensis Mill. architectural analysis for fuel modelling

Caraglio Y., Pimont F., Rigolot E.

in

Leone V. (ed.), Lovreglio R. (ed.).
Proceedings of the international workshop MEDPINE 3: conservation, regeneration and restoration of Mediterranean pines and their ecosystems

Bari : CIHEAM
Options Méditerranéennes : Série A. Séminaires Méditerranéens; n. 75

2007
pages 43-59

PINUS HALEPENSIS MILL. ARCHITECTURAL ANALYSIS FOR FUEL MODELLING

Y. Caraglio*, F. Pimont and E. Rigolot****
*INRA-CIRAD Unité de Modélisation des Plantes TA40/PS2, 34398 Montpellier, France
Phone: (+33) 4 67 61 65 48, Fax: (+33) 4 67 59 38 58
e-mail: yves.caraglio@cirad.fr
**Institut National de la Recherche Agronomique
Unité de Recherches Forestières Méditerranéennes
Equipe Prévention des Incendies de Forêts - 20 Avenue A. Vivaldi, 84000 Avignon, France
Phone: (+33) 4 90 13 59 35, Fax: (+33) 4 90 13 59 59
e-mails: pimont@avignon.inra.fr & rigolot@avignon.inra.fr

Abstract

A fire behaviour model based on the complete physical and multiphase approach has been developed in order to study fuel treatment efficiency at the wildland urban interface. The fire behaviour model is currently running in 2 dimensions (x, z) and requires a complete description of the vegetation in a 25 cm x 25 cm grid. In each elementary cell of this grid, fuel families have to be identified and quantified. The finest fuel families (twigs less than 6 mm and leaves or needles) have to be described in priority, because they are the most important fuel particles for fire behaviour. The main physical, chemical and thermical properties of each fuel family has to be known and the volume fraction enables to quantify its presence in a given cell.

Pinus halepensis stands are fire prone communities very common in South Eastern France. The architectural approach was applied to describe Pinus halepensis fine fuel distribution in order to build up inputs for the fire model.

Architectural analysis aims at a comprehensive and dynamic understanding of plant growth through the analysis of the major successive morphological events that happen during plant development from germination to death.

The plant architectural software AMAPsim developed by Cirad which relies on both qualitative and quantitative tree architecture description and leads to realistic 3D computing trees can be used to complement fuel characterization. From the computerized plant architecture model it is possible to access and extract various physical parameters. These spatialized data then could be used in fire propagation model.

This paper focuses on Pinus halepensis fine fuel characterization using AMAP tools. The AMAP methodology is presented as well as the data collected for plant growth and architecture modelling. Results on the main features of Pinus halepensis architecture are presented as well as Aleppo pine simulations of individual plants in order to extract fuel parameters. The first results of fire simulations in Aleppo pine stands are presented and the capabilities and limits of such an approach for fuel modelling are discussed.

Keywords: fuel model, fuel distribution, *Pinus halepensis*, architecture

INTRODUCTION

Mediterranean wildlands are regularly threatened by fire. Fuel build up in forest areas due to agricultural abandonment combined with the development of wildland-urban interface areas together with severe drought episodes over recent past years (global climatic change) have increased the potential fire hazard in such areas. Fire prevention becomes a priority and needs management tools. Because experimentation is often difficult, modelling approach is a way to prospect, test and compare mitigation operations like fuel-break design. The most popular fire models [1, 2, 3, 4] do not describe explicitly vegetation patterns. This approach is adapted for modelling fire behaviour in homogeneous vegetation layers but not in typical Mediterranean fuel complexes. Mediterranean vegetation presents several levels of heterogeneity, due to ecological factors (plants organisation in the community, natural stratification and horizontal gradient), fuel management effects (thinning, fuel break), and fuel distribution within individuals plants (vertical and lateral gradient in plant architecture, aggregation factor in shoot or twig). Physically-based fire propagation models like FIRESTAR [5, 6] or FIRETEC [7, 8] enable to take into account spatial fuel patterns and vegetation heterogeneity.

This study focuses on heterogeneity due to fuel distribution within plants. Fire propagation is mainly due to the thinnest elements of vegetation, essentially leaves or needles and smallest twigs. In the frame of the European program FIRESTAR, a methodology of fuel description based on destructive measurements was developed [9] using a physical 25 cm cell mesh. This method is mainly adapted to the description of shrubs and small trees, but cannot be easily used for mature trees due to their wide dimensions. In this last case, architectural approach [10] can be helpful, because it entails to build virtual trees, twig by twig and needle by needle.

Architectural analysis [11, 12] aims at a comprehensive and dynamic understanding of plant growth through the analysis of the major successive morphological events that happen during plant development from germination to death. The plant architectural software AMAPsim developed by Cirad [13] relies on both qualitative and quantitative tree architecture description and leads to realistic 3D computed trees that can be used to describe fuel spatial patterns. The method is applied here to *Pinus halepensis*, which is a wide-spread species in Mediterranean ecosystems [14]. *Pinus halepensis* communities are fire prone ecosystems with high post-fire regenerative abilities [15], which turns it as a priority vegetation type for fuel management.

In this study, the different steps to build architectural models are described, starting from morphological and architectural analysis, complemented with sampling and field measurements, and ending with the analysis and modelling phase. Part of the work on *Pinus halepensis* architectural analysis had already been described in [16]. With the new perspective of fuel modelling, additive measurements were implemented to improve the prediction of fine fuel volume fraction of our study site. From architectural model outputs, vegetation files were built to implement fire propagation simulation with FIRESTAR. Because FIRESTAR is so far a 2D model, only 2D data were extracted from virtual trees. Simulations on young and mature stands were run and analysed in order to assess the added value of the architectural approach for fuel description namely in a 3D fire modelling perspective.

MATERIAL AND METHOD

Plant architecture: general methodology and application to *Pinus halepensis* Mill. *(Pinaceae)*

a) General Methodology

Using 3D virtual plants in order to extract fuel parameters requires not only a realistic physiognomy but especially a realistic structure in terms of number and size of axes. In order to obtain such realistic virtual plants, three main steps are required.

Plant architectural analysis

Architectural analysis [11, 12] aims at a comprehensive and dynamic understanding of plant growth through the analysis of major successive morphological events that happen during plant development from germination to death. This approach points out the topological importance in morphological and growth expressions.

Field measurements and data analysis

Based on architectural description, specific botanical sampling and measurements are realised. They focus on the annual shoots that are the main plant structural entities.

All these field measurements are transferred to computer, as tree-structured data, using a specific coding language (Multi scale Tree Graph and AMAP Modelling Language, [17]) that allows to explore and to analyse these measurements with AMAPmod software tools [18]. Methods for analysing plant architecture are based on stochastic modelling of meristem activity. Growth, branching and mortality are the elementary processes taken into account [19]. These methods provides means for quantifying the morphological trends identified by the qualitative architectural analysis.

Simulation of tree architecture

Using concepts derived from architectural analysis and comprehensive approach of plant development, simulation software called AMAPsim [13] is mainly based on the concepts of “morphological trends” and “physiological age” [10]. Plant development is simulated using an automaton whose successive states are ordered along a “reference axis” [20]. This automaton mimics (*i*) the physiological ageing of meristem expressions and other botanical entities during ontogeny, and (*ii*) the morphological trends that exist at different levels of organization within the plant [21]. A software called ForestFire based on a spatial discretisation method was used to extract different classes of virtual plant elements according to species, diameter class, type of organ, dead or alive parts.

b) Life history and morphological traits of Aleppo pine

Aleppo pine is a coniferous Mediterranean tree. Its monopodial and orthotropic axes show rhythmic and indeterminate growth. Annual periodic growth results in new part of leafy axis (*i.e.* growth unit **GU**, [22]). Branching is expressed one year after the arising of lateral buds which are grouped in a tier of lateral axes at the upper part of each growth units. Aleppo pine follows architectural Rauh's model as defined by [23]. Aleppo pine architectural characteristics can be described during its ontogeny. From germination to juvenile stage, apical meristems of Aleppo pine axes produce internodes and leaves. The form and morphological features of leafy organs change all along the stem (Figure 1a) from photosynthetic aciculate leaves (Figure 1b) to scale leaves (Figure 1c). Then photosynthetic assimilation is realized by two big leaves ("needles") borne on very short lateral axes ("brachyblasts") localised in the axil of scale leaves ("bracts"). This modification is completed two or three years after germination.

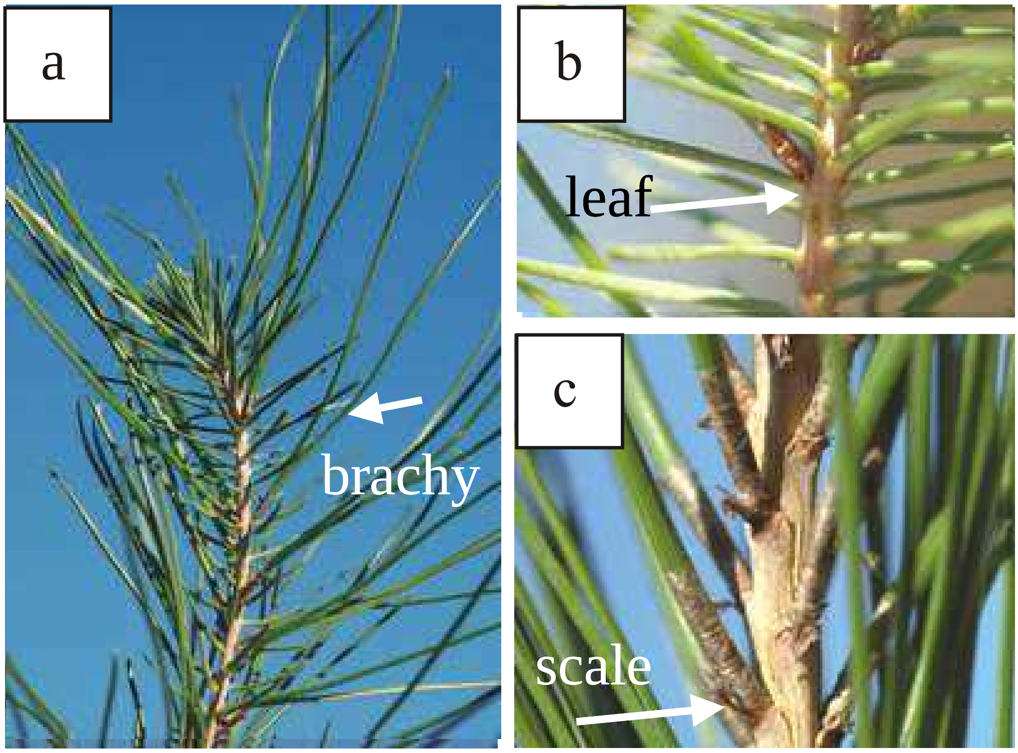

Fig. 1. Young stem showing scarcely brachyblasts (a) and the transition between leaf (b) and scale (c) in the axil of which a brachyblast is developing.

The axes growth extension presents rest phases more or less marked during the first years (summer and winter period, dry or cold conditions) and are materialized by a rosette of young leaves at the extremity of the axis. These rest phases become regularly marked by a scaly apical bud as the brachyblast expression becomes generalised.

Young Aleppo pines show a polycyclic behavior [24]. Within a year, an annual shoot (**AS**) can produce one or more successive flushes (growth units), the number of which varies from one to four according to (i) location within the plant structure and (ii) ecological conditions. The general growth unit organisation is shown on figure 2a. Nevertheless, each GU shows a particular set of morphological characters according to its position along the annual shoot (Figure 2b). Morphological characters of Aleppo pine GU had been quantified by [16], who showed that the first GU produced in the year was always the smallest and bore the female cones. Another feature was the length ratio between the leafy (zone 2) and the scaly part (zone 1).

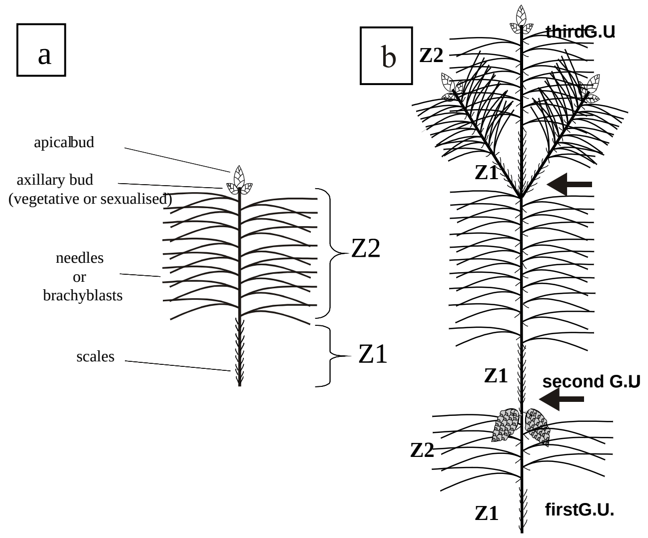

Fig 2. (a) General growth unit organisation showing leafy zone (Z2) and scaly zone (Z1). (b) Tricyclic annual shoot organisation (three flushes in a year).

A strong apical dominance leads to a highly organised structure around the main stem. All Aleppo pine axes are orthotropic and with rhythmic growth and branching. Nevertheless, morphological differences between axes are significant and allow to clearly identify trunk, branches, twigs, and especially in regard to polycyclism and sexuality features (Figure 3). The fully established branched system can then be summarised in terms of a very simple set of axes categories which defines the specific elementary architecture of each plant architectural unit [10] representing the most theoretical tree hierarchy and its fundamental organisation.

trunk	branches	twigs	ramlets	short axes (brachyblasts)
orthotropic	orthotropic	orthotropic	orthotropic	ageotropic
indefinite growth	indefinite growth	indefinite growth	~definite growth	definite growth
	delayed branching	delayed branching	delayed branching	immediate branching
three to ten axillary productions	two to six axillary productions	until two axillary productions	no axillary production	no axillary production
female cone	female cone	male cones	male cones	not sexualised
polycyclic up to four cycles	polycyclic up to three cycles	polycyclic up to two cycles	monocyclic	monocyclic

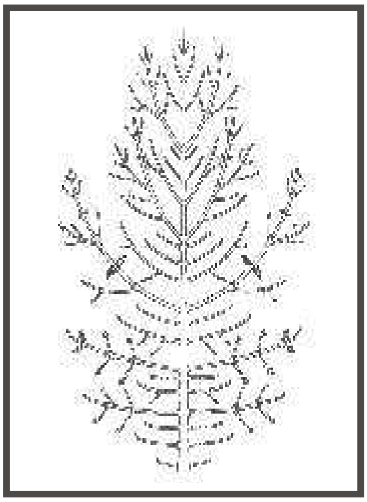

Fig. 3. Architectural unit of *Pinus halepensis*: architectural elements characteristics and schematic representation of elementary architecture

Atypically in the coniferous group of pines, adult trees of Aleppo pine (like Scot pine) edifies a real crown using a reiterative strategy [11]: it duplicates its elementary architecture. This phenomenon appears through the possible development of branches (one or more) as strong as the main stem. It results in a perennial fork which constitutes the base of the tree crown. This phenomenon is repeated through times: reiterated structures are each time smaller and AS organisation becomes progressively less branched, more frequently sexualised (female cones) and bicyclic (two GUs). With ageing, reiteration occurs more frequently. ASs are even smaller and finally end as monocyclic, male and unbranched shoots. On unbranched axes of the old Aleppo pine crown, new axes can sometimes develop from apical meristem of specialized determinate brachyblast. This mechanism offsets the lack of lateral buds with this brachyblast dedifferentiation. Finally, figure 4 summarizes the global architectural sequence of development in association with AS organization of main axes.

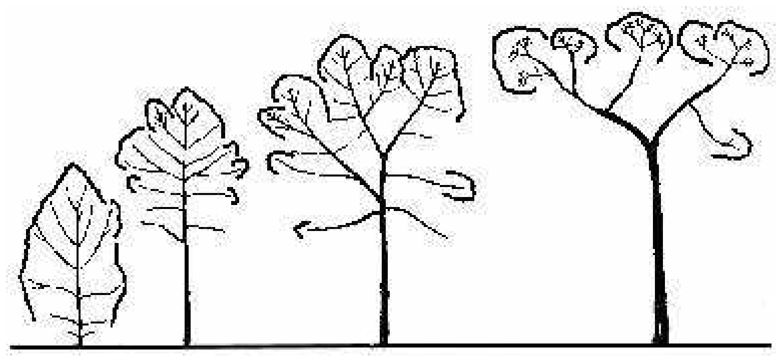

Fig. 4. Architectural sequence of development of *Pinus halepensis*: (from left to right) architectural unit step, main stem duplication, crown edification (adult tree), crown size stabilisation (mature tree).

Calibration

The existing architectural model using AMAPsim software had been built with data on *Pinus halepensis* from various sites [16]. Volume fractions of finest fuel families are significant parameters for fire behaviour. Since architectural model was not designed to estimate accurately needles number per unit of volume, complementary measurements were performed by CIRAD-AMAP and INRA-URFM-PIF in January 2005.

a) Data collection

Six pines were selected in a mixed pine-oak stand close to Pic Saint Loup mountains in South Eastern France (43°47'36” N ; 03°50'11” E). Well growing trees with no evidence of disease were selected among a wide range of DBH (Table 1). Pine age was determined by sampling a disc on each stem. After drying and sanding down of the discs, rings were counted to deduce tree age. Surprisingly, despite of the wide range of tree diameters, five pines out of six were nearly 35 years old.

Table 1. Characteristics of the 6 sampled trees

Diameter class (cm)	*Tree*	*DBH (cm)*	*Height (m)*	*HCB (m)*	*Age (years)*
[10-20[	1	17.0	13.0	7.0	34
	2	16.3	14.0	6.7	39
[20-30[	1	24.1	14.7	5.6	37
	2	21.0	12.0	6.8	38
[30-40[	1	32.8	15.8	7.0	39
	2	34.6	17.0	9.0	55

DBH: Diameter at Breast Height ; HCB: Height of Crown Base

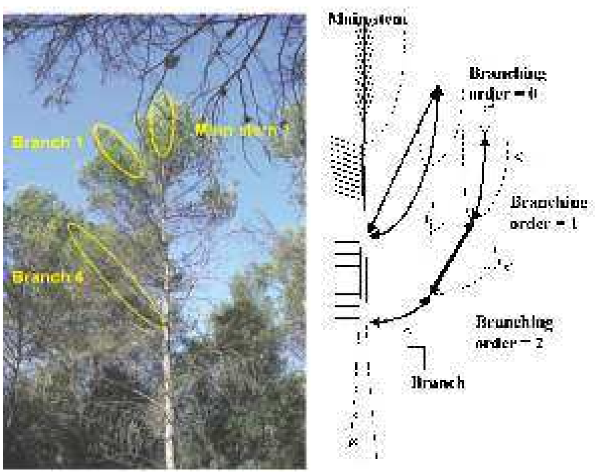

Fig. 5. (a) Sampling parts of the tree. (b) Description of branching system.

On each sampled tree, the main stem and four main branches were selected (one on each quarter of the living crown height, Figure 5). When tree had several main stems, up to 3 of them were selected. Main stems were noted 0 and branches were noted from 1 to 4 from the top to the bottom of the crown. Thus, low values of branch type correspond to main branches. On each main branch or stem, 4 secondary branches were selected, with branching order varying from 0 (apical shoot of the main branch) to three (Figure 5b). All growth units of all leafy annual shoots of each secondary branch were described in the following way (Figure 2a):

- Measurement of scaly zone (Z1): length,
- Measurements or estimations on leafy zone (Z2): length, number of needle fascicles still present and visual estimation of the fraction of fallen needles.

Diameter of annual shoots and branches were also measured.

To recognize the two kinds of structural limits (growth unit and annual shoot), morphological markers were essentially used. The most useful was the presence of tier of branches that delimited GUs. The presence or the scars of female cone indicate the first GU of an AS. When no sexuality was expressed, tier of branches with diameter bigger than following or preceding revealed the limit between two AS. Strongest branches were generally born on the last GU of the year (traumatism excepted) and issued from buds which were waiting during winter period (delayed branching, [24]). When parts of unbranched axis were measured, the delimitation of AS required the observation of scales scars (corresponding to bud form). Because unbranched GU frequently corresponded to monocyclic AS, the identification of scales scars was sufficient (Figure 6c). Sometimes polycyclic AS doesn't bear female cone or could be unbranched ; in this case, the length of scales scars internodes was considered: it is larger in the GU limit (Figure 6b) than in the AS one (winter, Figure 6a). Male catkins were also used: they let raised scars that delimited the GU of monocyclic sexualized (the spring one, Figure 6d). The sequence of GU length is also an indicator, the first GU being generally the shortest. All these characters have to be combined together.

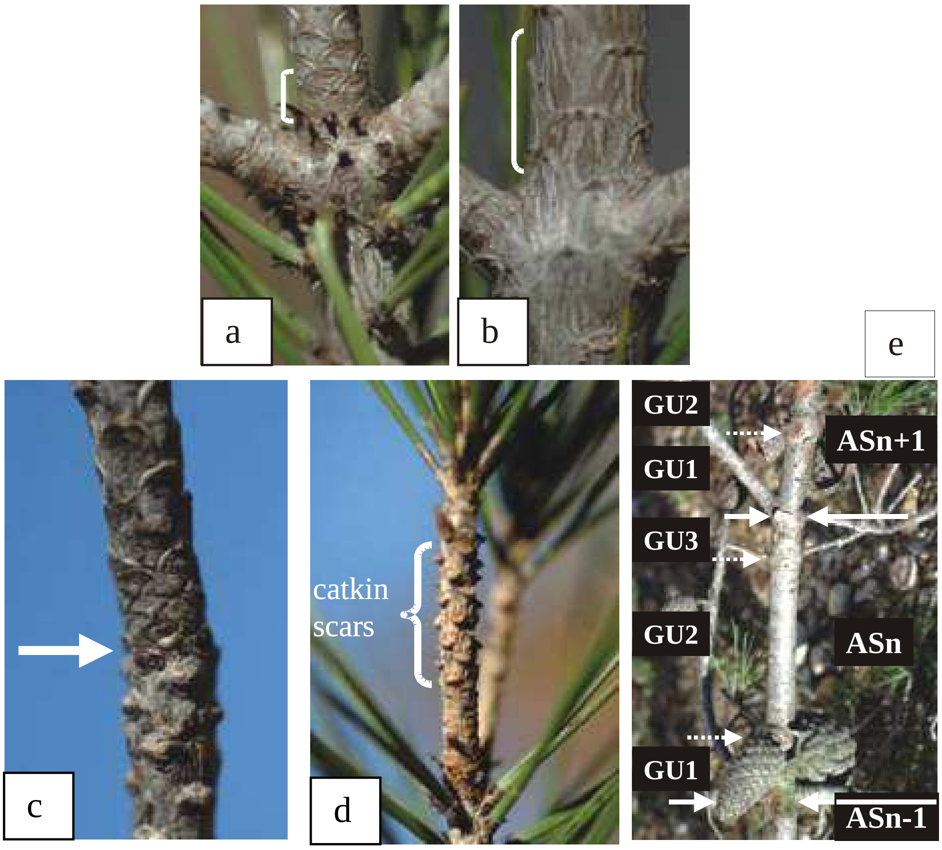

Figure 6. Inter (a) and intra (b) annual limits. (c) Limit on monocyclic unbranched annual shoot. Specific scars let by male catkins on monocyclic annual shoots. (e) Tricyclic annual shoot illustrates female cones on the first shortest growth unit (GU1), largest branches on the last growth unit (GU3) of the annual shoot.

b) Data analysis

Data analysis was focused on the main architectural characteristics in order to improve the existing *Pinus halepensis* model in a fuel description perspective. When no evidence of fallen needles were found on a given growth unit, **internode length** was calculated on the base of the ratio of the Z2 leafy part length and the number of fascicles. Internode length is the key factor to predict needles number. Indeed, AMAPsim simulates the l**ength of Z2 leafy part** and calculates the number of fascicles with the base of internode length. In order to analyse the distribution of lengths of the leafy part of the growth unit, histograms were built and negative binomial regression were fitted using AMAPmod software. **Annual shoot length** (sum of length of the different growth units for a given year) was calculated. Annual shoot length was fitted as a function of branching order of the secondary branch the shoot is on (Figure 5b). Annual shoot length was also fitted as a function of branch type (from 0 for main stems, to 4 for lowest branches).

Frequency of number of growth cycles per year was calculated. Presence of **polycyclism** on annual shoots was modelled with logistic regression (R software) as a function of branching order. Percentage of fascicle presence as a function of age of shoot were also calculated using a logistic regression. It entailed to evaluate **life period of needles**.

c) Extractions and calibration

All these data were compared to Aleppo pine AMAPsim model extractions. Because a virtual plant was computed by AMAPsim software, its equivalent topology could be obtained as a multi-scale tree graph (MTG) [17], a tree structured data compatible with statistical analyse (AMAPmod software). Virtual plant were computed at the same age than fields observation (35 years old). Among many stochastic realizations, three virtual trees were selected (one in each sampled diameter class). From the MTG of each virtual tree, same data than field measurements were extracted. In order to calibrate the model, but to minimize the number of parameters to modify, analyse was focused on the relation between number of leaves and the GU leafy part length (Z2). When comparisons were not satisfactory, parameters of the models were changed to fit better with sampled data.

Fuel simulation and fire simulation

a) Fuel simulations

In the FIRESTAR fuel modelling process, fuel is described with several fuel families: leaves and needles (dead and alive) and twigs split in several classes of diameter. Only the finest fuel classes are taken into account: very thin (<2mm), thin (2-6mm), medium (6-25 mm) [9]. FIRESTAR vegetation files describe, for each fuel family, the properties (Table 2) and volume fraction of vegetation in a 2D mesh. Mesh size is mostly of 25 cm, except in the first 50 cm height layer were the mesh size is 5 cm. These data were collected in the frame of FIRESTAR European program by INRA Avignon.

Table 2. Main properties of different fuel families

Family	***Area to volume ratio (m^2/m^3)***	***Density (kg/m^3)***	***Fuel moisture content***
P. halepensis needles	10 000	850	100 %
P. halepensis small twigs	1000	900	100 %
Q. coccifera leaves	6000	820	70 %
Quercus coccifera twigs (0 to 2 mm)	3000	900	70 %
Quercus coccifera twigs (2 to 6 mm)	1000	900	70 %

Extractions of 10 and 35 year old pines modelled by AMAPsim, were used to build vegetation files. Main characteristics of these trees are described in table 3.

Table 3. Characteristics of virtual trees used for vegetation files

	Age (years)	***Height (m)***	***HCB (m)***	***Average (max) VF of needles***	***Average (max) VF of twigs***
Pine10	10	2.25	0.45	330 (1274)	19 (118)
Pine35	35	9.75	3.25	75 (1467)	6 (331)

2D slices in the medium part of the crown of a virtual pine were extracted. The same crown pattern was used to create a virtual scene with the expected tree density for both young and mature virtual pines (Figure 7a and 8a with a 60% cover). In the case of mature pine, a homogeneous kermes oak (*Quercus coccifera*) understorey of 75 cm high was displayed under the Aleppo pine canopy. *Quercus coccifera* properties are described in table 2. Moreover, the canopy was present only on the second half of the domain, in order to create an ignition zone of pure shrub land. To evaluate the effect on fire behaviour of fine fuel distribution within pine crown, we also built two other representations of pine canopy with coarse crown shapes: a stand with several simplified pine crowns (rectangular boxes of homogeneous vegetation with same height, same width and same average volume fraction than virtual trees, Figure 7b and 8b), and stand with an homogenized crown layer (homogeneous layer with same height, Figure 7c and 8c). These different fuel models were three different ways to represent a same total fuel load.

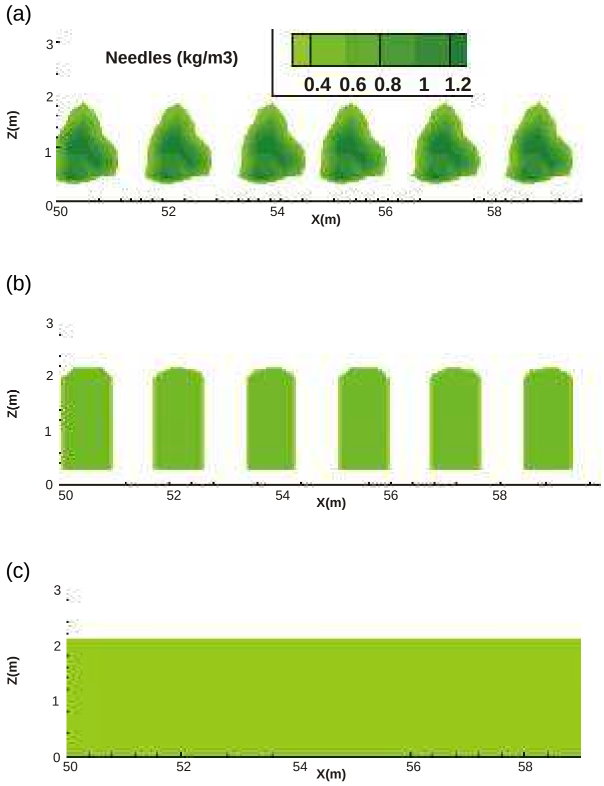

Fig. 7. Bulk density of young pines stand with (a) virtual trees, (b) homogenized trees, (c) homogenized stand, in FIRESTAR input file

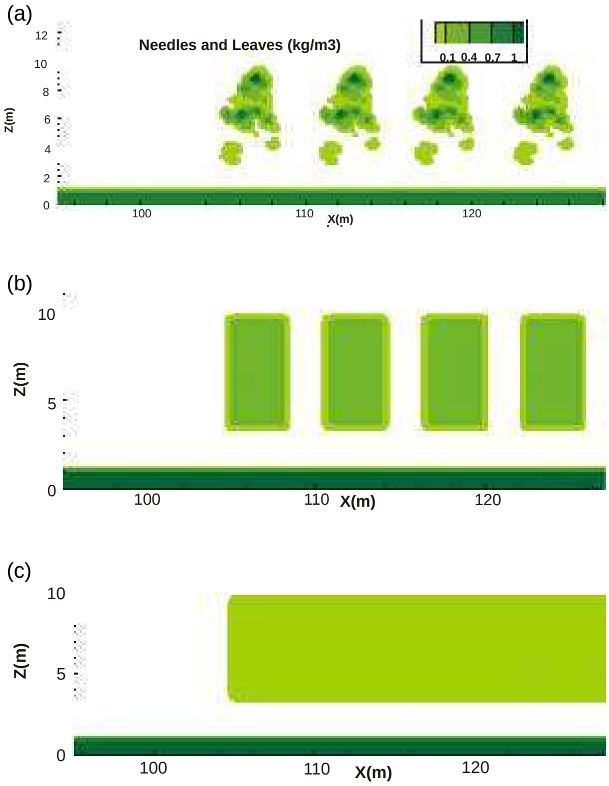

Fig. 8. Bulk density of mature pines stand with (a) virtual trees, (b) homogenized trees, (c) homogenized stand, in FIRESTAR input file

These files were built for several values of cover fraction: 25%, 40%, 60%, 80% and 100%.

In the case of mature stand with understorey, a pure shrub land of kermes oak was also added in order enable surface fire spreading.

b) Fire simulations

FIRESTAR physically based fire propagation model is a 2D fluid mechanical code [5]. It includes radiative transfer and description of chemical reactions (evaporation, pyrolysis and combustion). Simulations were run on a SGI computer with four processors at INRA-URFM-PIF Avignon. Outputs were analysed with Tecplot 9.0. Domain dimensions for fire simulation with FIRESTAR 2D were 225 meters length and 40 meters height. Wind conditions were selected with a log wind profile and a value of 6 m/s at 10 meter above ground level.

To compare fire characteristics in different cases, rate of spread, flame height and fire intensity were analysed as a function of pines cover fraction. These indicators are the most used in literature [25, 26]. Rate of spread was calculated following the most downwind position of isotherm 700K. Flame height was calculated as the highest point of isotherm 700K. Power was calculated by the model using gas combustion process. In the case of mature stand, crown damage was also analysed by monitoring the consumption of crown fuel.

RESULTS

Aleppo pine architectural simulations

AMAPsim software can generate different steps of crown construction (Figure 9). For each step, many stochastics realizations are computed (Figure 10). In these virtual plant, the polycyclism, the length of GUs, the number of branches per tier vary according to age of axes and location within tree. Combined with the self pruning of branches, tree crown architecture was varying in structure and size. The sexuality had not been taken into account yet.

Fig. 9. *Pinus halepensis* crown architecture development. From left to right, the same individual at respectively 10, 20, 30 and 40 years old.

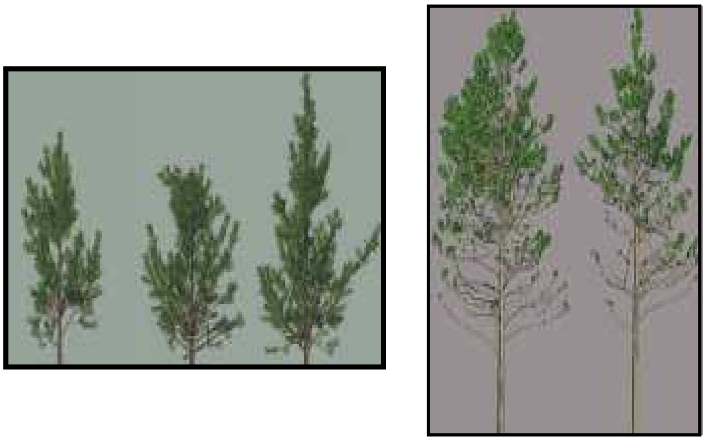

Fig. 10. *Pinus halepensis* crown architecture variability at 10 (left) and 30 (right) years old

Calibration and validation of *Pinus halepensis* model

a) Calibration results : Temporal Unit Length

Comparison of internode length calculated with our sample to values extracted with AMAPsim software on previous Aleppo pine architectural model, showed an overestimation of internode length with AMAPsim. Consequently the parameters controlling internode were changed. Figure 11 shows that, after this calibration, a small overestimation can still been observed for long growth unit, but results are much better.

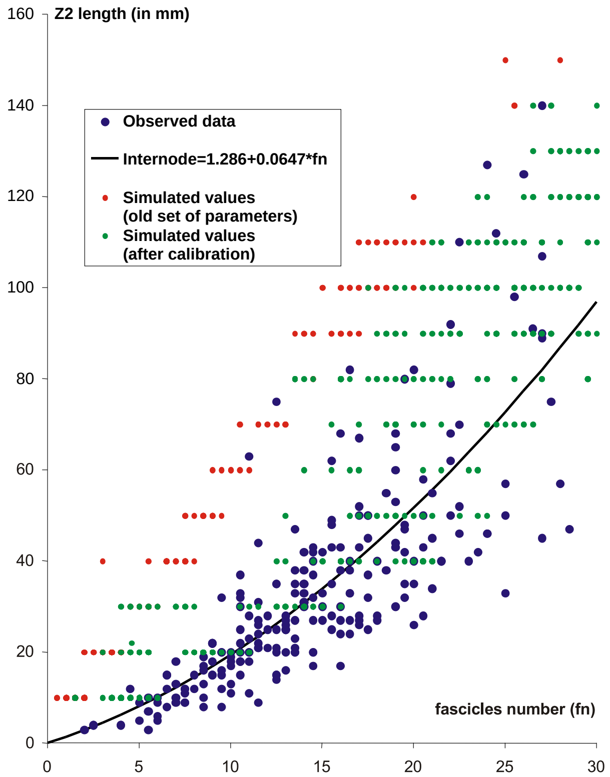

Fig. 11. Calibration of internode length after comparison between observed and simulated data

b) Validation

Concerning **length of annual shoot**, histograms showed same kind of distribution for observed and simulated data. Nevertheless, Z2 length between 10 and 20 mm was overpredicted by the model (Figure 12). Annual shoot length was sensitive to branching order and branch type (Figure 13a and 13b). Data simulated by AMAPsim were quite close to experimental data.

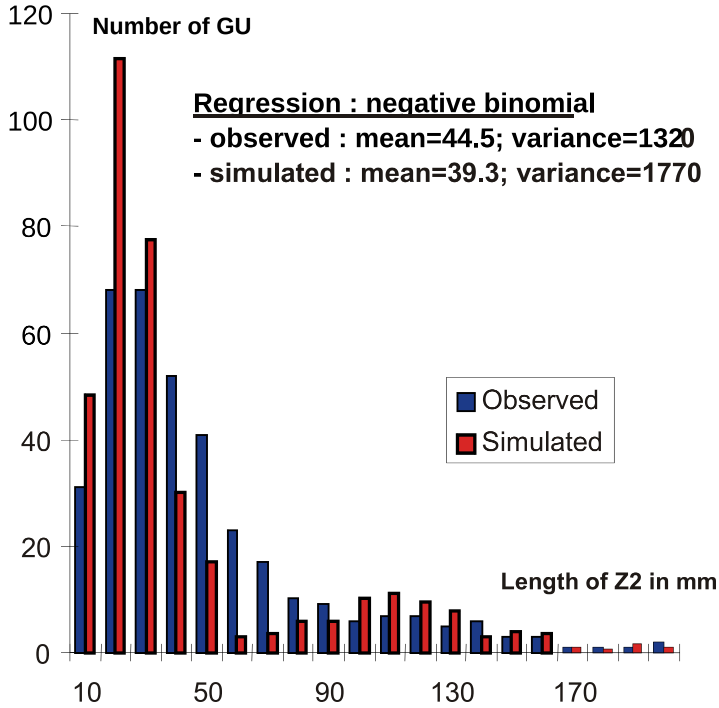

Fig. 12. Comparison of distribution patterns of Z2 length between observed and simulated data

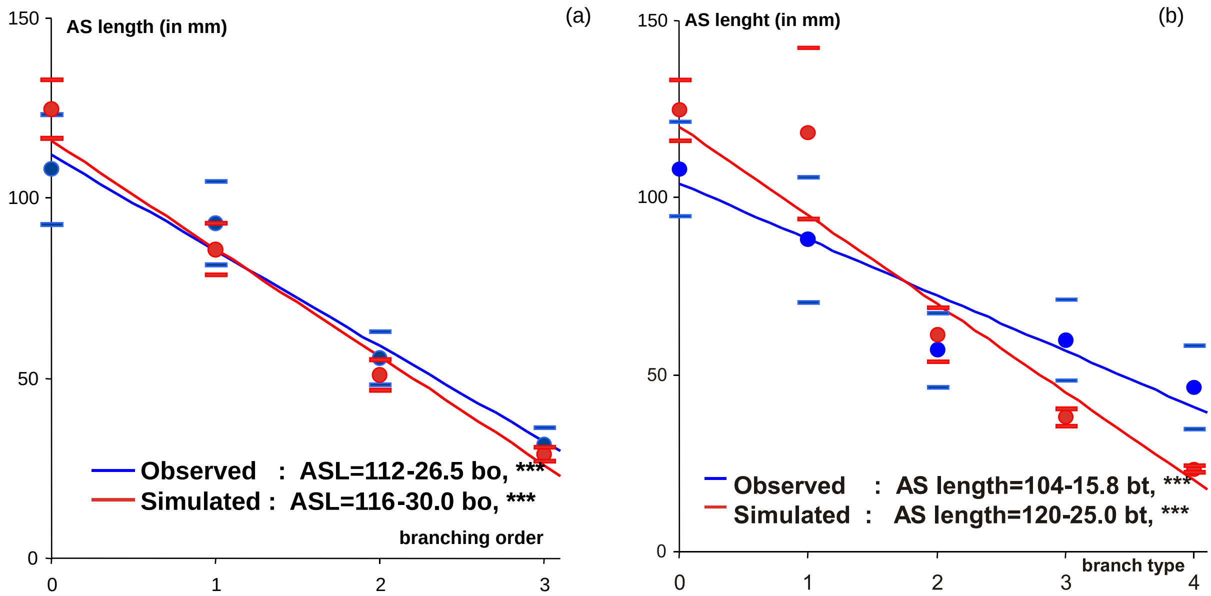

Fig. 13. Comparison between observed and simulated data for annual shoot length trend as a function of branching order (a) and branch type (b).

Polycyclism decreased significantly with branching order. Simulated data showed the same trend but not the same magnitude, especially for law branching order (Figure 14). AMAPsim predicted only 20% of polycyclism against 28% in observed data (Figure 15). The logistic regression of **life period of needles** provided very satisfactory results, leading to a life estimation of 2.56 years (Figure 16). In AMAPsim model, age of needle were constant (3 years). Because we did these measurements after the 2003 drought, we decided not to modify the parameters of the model.

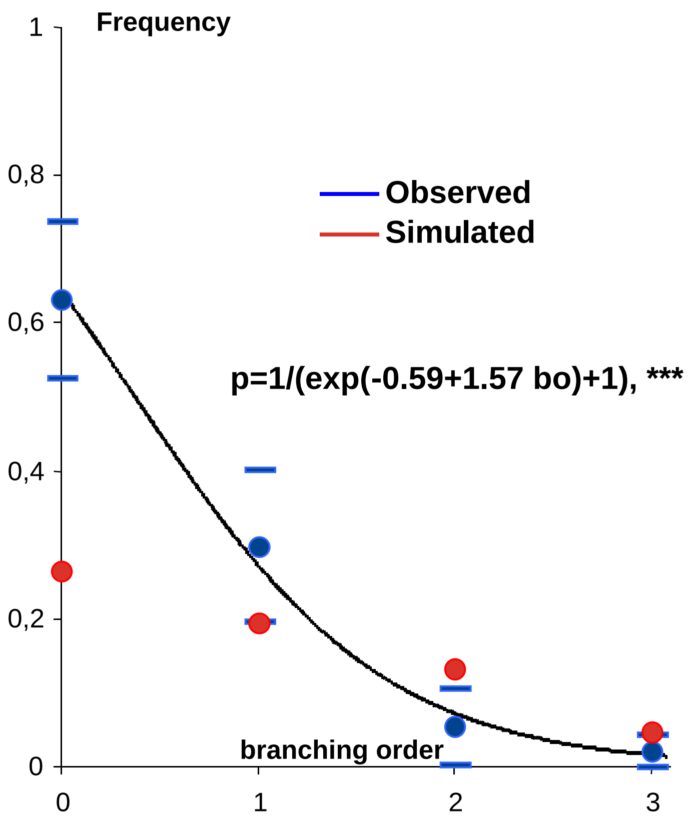

Fig. 14. Comparison between observed and simulated data for frequency of polycyclism as a function of branching order.

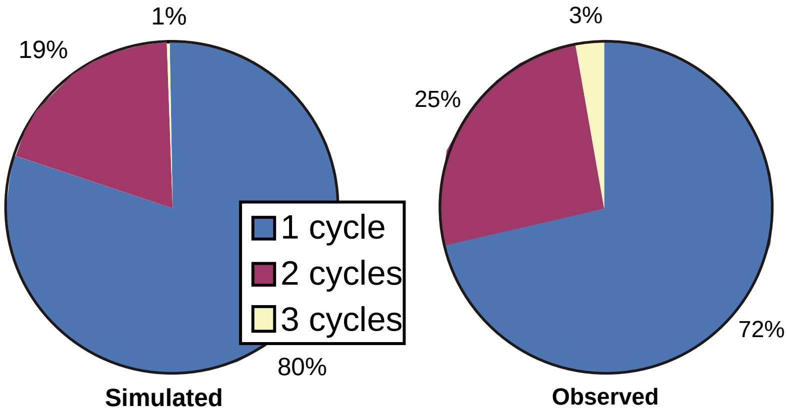

Fig. 15. Compared frequencies of annual shoot cycle number

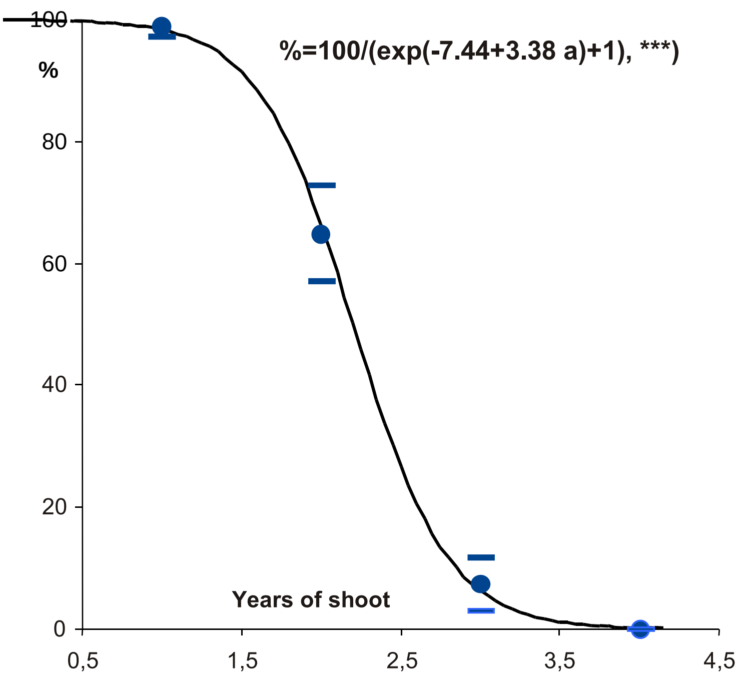

Fig. 16. Proportion of needle presence as a function of needle age

Fire propagation in different types Aleppo pine stands

Analysis of simulated fire rate of spread (ROS) showed that in few cases, fire stopped after a propagation of less than 100 meters. These cases corresponded to the lowest cover fraction value. In virtual trees stand, rate of spread decreased with cover fraction. When fire propagated, ROS was twice higher for homogeneous trees and stand than for virtual trees (Figure 17). Moreover, the threshold of cover fraction for fire propagation up to the end of the domain was not the same with the three representations: between 25 and 40% for virtual trees and between 40 and 80% for homogeneous cases.

Average flame height was not affected by the cover fraction (data not shown). Nevertheless, flames were almost twice higher in homogeneous trees and in homogeneous stands (around 6 m) than in virtual trees (around 3.5 m).

Fire intensity tended to increase with cover fraction. For this variable also, values were twice higher for homogeneous cases (Figure 18).

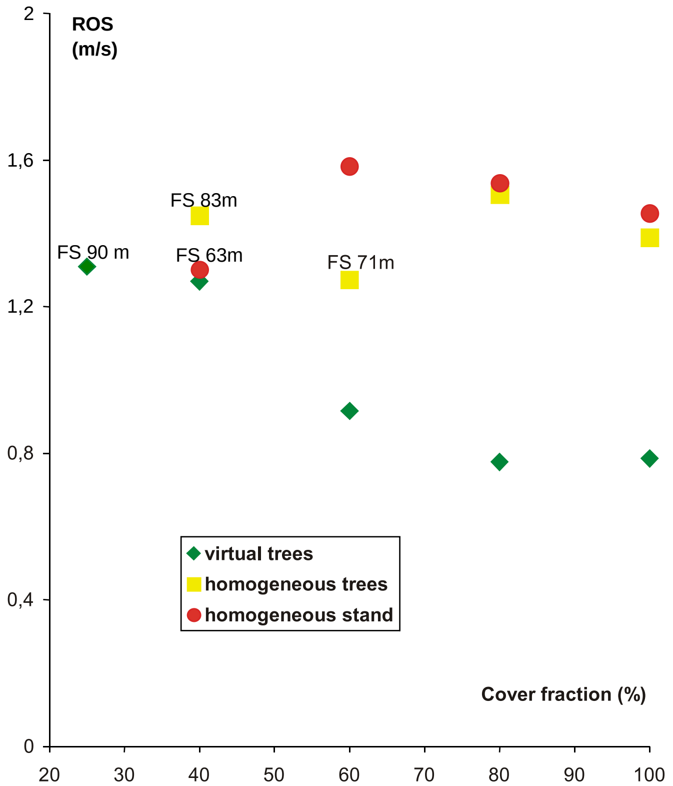

Fig. 17. Rate of spread (ROS) of the 3 ways to represent vegetation, as a function of cover fraction (FS # m means that the fire stopped after # meters of propagation)

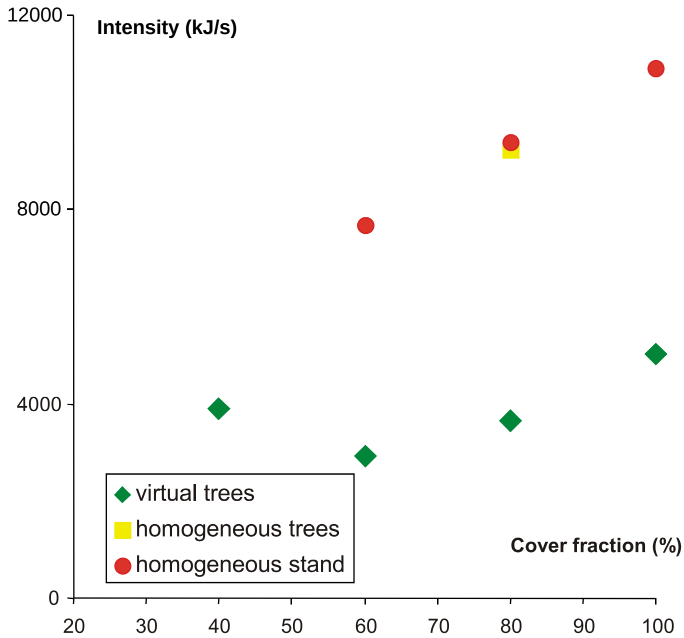

Fig. 18. Fire intensity for the 3 ways to represent vegetation, as a function of cover fraction (data were not represented when fire stopped).

In the mature stands, very few differences could be seen on fire behaviour according to the three main indicators (data not shown). Indeed, the fire front in mature stand was very close from the case without canopy (plotted in black in figure 19). Nevertheless, small accelerations due to torching in the crown could be observed. First crowning started respectively 75 meters and 100 meters after stand edge for homogeneous and virtual tree stands.

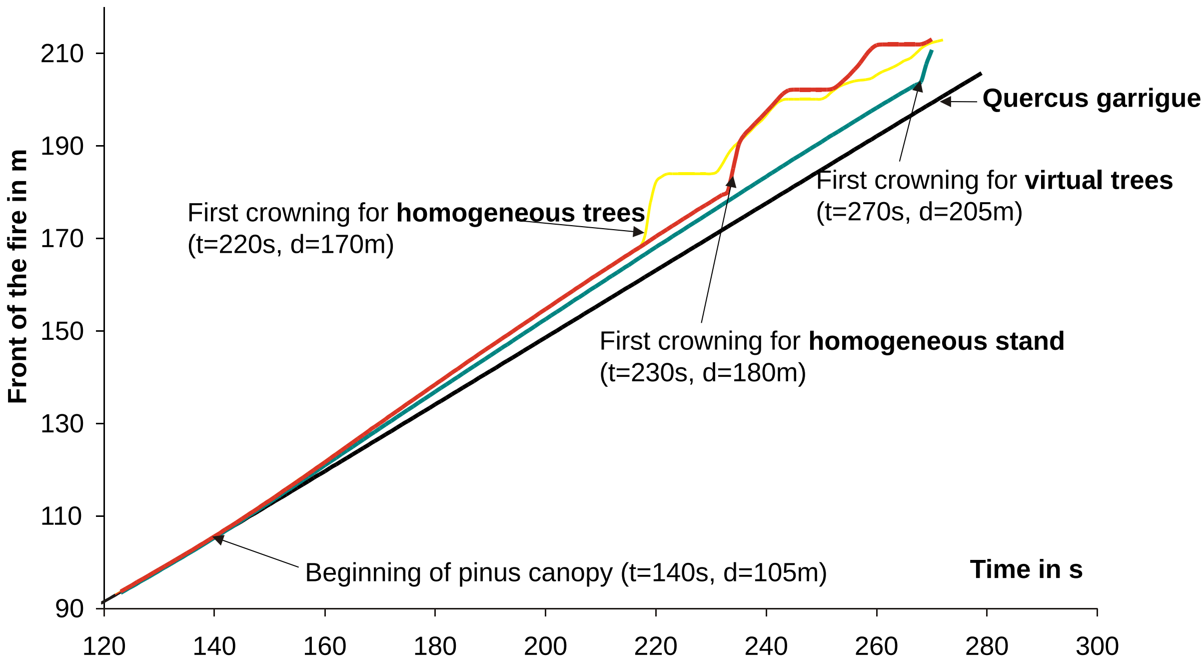

Fig. 19. Distance travelled by the fire, as a function of time for the 3 ways to represent vegetation (cover fraction 80 %).

Further analysis showed that vegetation consumption (data not shown) was different when trees were virtual or represented in an homogeneous way. Fuel consumption was higher in the homogeneous canopy than in the virtual trees stand.

DISCUSSION

Aleppo pine architecture

This study contributed to better calibrate the Aleppo pine architectural model namely for the estimation of needles number and crown size.

Internode calibration on a given study site is an important step to improve local quality of model prediction. Our study showed that internode length could vary from site to site and that its calibration could be improved by light field measurements. The response of other components of tree architecture was satisfactory with regard to field observations, even without changing the parameters of initial model of Aleppo pine. For instance, the effect of branching order and branch type on annual shoot length was satisfactory both in trend and magnitude without specific calibration. The tree organisation was stable enough from one site to another. Our recommendation would be to use the current set of parameters without further improvement.

Nevertheless some parameters like polycyclism seemed to vary from site to site and then would need further calibration with a wider range of local conditions or annual meteorological sequences [27]. However volume fraction prediction by the mean needle number is probably less sensitive to polycylism frequency than other allometric parameters. Total shoot length and number of needle per length unit are the most important factors to explain total number of needles.

Needle life period needs to be better appraised by further studies, taking into account normal meteorological sequences.

Both range of values and spatial distribution variability seemed reasonable. Moreover, even though very few references could be found in literature, average volume fraction was in the same order of magnitude than field data derived from [28] (LAI and direct measurements).

After calibration, one can be rather confident in using extracted volume fractions for fire simulations.

Fire behaviour

In young pine stand, fire propagation stopped when the cover fraction was too low. It seemed very reasonable that when the distance between trees increased, it raised a limit after which propagation was not possible any more [29]. ROS decrease with cover fraction was in agreement with [30]. Indeed, these authors showed that ROS was decreasing with volume fraction (called packing ratio in their publication). But the more interesting point was that ROS were very different between virtual trees compared with homogeneous cases (trees and stands). This result encourages us in the direction that local heterogeneity can influence the propagation. With virtual plant stands, fire propagation remained very smooth and with a lowest value than homogeneous cases. In fact, it seemed to behave like in an homogeneous canopy of higher density than its average density. We can notice that flame height and fire intensity were significantly different too.

In the mature stand, very few differences could be seen on fire main indicators. Indeed, model predicted a propagation driven by the surface fire, with only sparse torching. In this case, the way to describe the vegetation affected only the way the canopy was damaged by the surface fire. Torching appeared latter and was less intense in virtual trees stand than in homogeneous situations. A deeper analysis showed that it was due to vertical distribution of volume fraction in the canopy. Indeed, the canopy base was very light in virtual trees compared to homogeneous cases (trees were more leafy at the top and middle than at the bottom). This provided less drag between the understorey and the canopy in virtual trees stand. Thus, flow was faster. For this reason, flame was more bent and cooled, which provided less torching possibilities. Moreover, foliage at the bottom of the crown was not dense enough to entail the inflammation of the whole canopy as it could appear in homogeneous cases.

Our approach was here considerably limited by the two dimensions of the fire model. Indeed, fuel description in two dimensions increases artificially fuel heterogeneity along the direction perpendicular to fire propagation.

CONCLUSION

Architectural approach entails to build virtual trees of different ages and a virtual sampling under minimal measurements for site calibration. It allows to extract quickly spatial patterns of fuel loads within a tree. It is a promising method for fuel modelling in case of trees, where destructive methodology seems less appropriate [9]. This modelling approach is even possible on shrubs. Nevertheless, in this case, destructive measurements are rapidly applicable and in fact more appropriate to describe the horizontal pattern of shoots in the stand [31].

In this study, the variations of plant architecture of *Pinus halepensis* due to ecological conditions were taken in account through site calibration. Internode values were changed in the model according to field measurements. A higher polycylism rate than in previous sampling was also observed. Two modelling strategies can probably permit to minimize some of calibration aspects. The first consists in general study and analysis of architecture responses to external factors (like drought, wind, soil conditions) using more physiological hypothesis (see Greenlab approach [32, 33]). The second consists in using plant structure functions that permit to take into account the influence of stand density, species arrangement at the community level, taking into account phototropism and competition [34]. Both strategies can help to quantify better architectural parameters *a priori*.

Fire simulation results are too sparse to conclude on the wide and complex topic of heterogeneity. It was not the aim of this paper, which was a preliminary study to appraise the benefit of the architectural approach for fuel modelling. Moreover, our approach was limited here by the two dimensions of vegetation description and fire modelling. Nevertheless, this approach suggested that small scale heterogeneities could modify significantly main fire properties specially when driven by a dense heterogeneous vegetation. Otherwise, small scale heterogeneities only affected fire effects on pine crowns.

In conclusion, the architectural approach is a promising method for fuel modelling, very complementary to the FireStar classical method [9]. Other shrubs and trees species are being described taking into account variations of plant architecture due to ecological conditions in order to simulate complete Mediterranean communities with physically based fire propagation models.

Acknowledgments

We are grateful to Philippe Petit for field and laboratory assistance during this work.

REFERENCES

[1] Andrews P.L. (1986). BEHAVE: Fire behaviour prediction and fuel modelling system - BURN subsystem, part 1, *USDA Forest Service, Research paper INT-194*, 130p.

[2] Noble I.R., Bary G.A.V., Gill, A.M. (1980). "McArthur's fire danger meters expressed as equations", *Australian Journal of Ecology,* 5, pp.201-203.

[3] Cheney, N.P., Gould, J.S., Catchepole, W.R. (1998). "Prediction of fire spread in grasslands", *Int. J. Wildland Fire* 8 (1), pp.1-13.

[4] Forestry Canada Fire Danger Group, Development and structure of the Canadian forest fire behaviour prediction system. *Information report ST-X-3. Forestry Canada, Ottawa*, 1992, 63p.

[5] Morvan D., Dupuy, J.L. (2001) "Modeling Firespread Through a Forest Fuel Bed Using a Multiphase Formulation", *Combustion and Flame*, 127, pp.1981-1994.

[6] Dupuy J.L., Morvan, D. (2005). "Numerical study of a crown fire spreading toward a fuel break using a multiphase physical model", *Int. J. Wildland Fire,* 14 (2), pp.141-151.

[7] Linn, R.R., Reisner, J., Colman, J.J., Winterkamp, J. (2002). "Studying wildfire behavior using FIRETEC". *Int. J. Wildland Fire* 1, pp.233-246.

[8] Linn, R.R., Cunningham, P. (2005). "Numerical simulations of grass fires using a coupled atmosphere-fire model: basic fire behavior and dependence on wind speed", *Journal of Geophysical Research-Atmosphere* 110 (D13), D13107.

[9] Cohen M., Rigolot, E., Valette, J.C. (2004). From the vegetation to the inputs of a fire model: fuel modelling for wildland-urban interface management. *Warm International Workshop on "Forest Fires in the Wildland-Urban Interface and Rural Areas in Europe: an integral planning and management challenge", Athens, May 2003.* 2004, pp.113-120.

[10] Barthélémy D., (2003). Botanical background for plant architecture analysis and modeling. *In* Hu B., Jaeger M. (Eds), *Plant growth modelling and applications* (PMA03), Proceedings of the 2003' International Symposium on Plant Growth Modeling, Simulation, Visualization and Their Applications, Beijing, Chine, 13-16 octobre 2003. Beijing: Tsinghua University Press, Springer; pp. 1-20.

[11] Barthélémy D., Edelin, C., Hallé, F. (1989). Architectural concepts for tropical trees. *In : Tropical Forests: Botanical dynamics, speciation and diversity*, L.B. Holm-Nielsen and H. Baslev (Eds.), Academic Press, London, pp.89-100.

[12] Hallé F., Oldeman, R.A.A., Tomlinson, P.B. (1978). Tropical trees and forests. *Springer Verlag*, Berlin; 441 p.

[13] Barczi J.F., de Reffye, P., Caraglio, Y. (1997). Essai sur l'identification et la mise en oeuvre des paramètres nécessaires à la simulation d'une architecture végétale : le logiciel AMAPsim. *In*: *Modélisation et Simulation de l'Architecture des Végétaux*, Bouchon J., Reffye P. de, Barthélémy D. Eds.; Paris (FRA) : Science Update, INRA Editions, pp.205-254.

[14] Quézel P. (2000). Taxonomy and biogeography of Mediterranean pines (*Pinus halepensis* and *P. brutia*). *In*: Ne'eman G. and Trabaud L. (eds), Ecology, biogeography and management of *Pinus halepensis* and *P. brutia* forest ecosystems in the Mediterranean basin. Backhuys Publishers, Leiden, The Netherlands, pp.112.

[15] Ne'eman G., Goubitz,S., Nathan, R. (2004). "Reproductive traits of *Pinus halepensis* in the light of fire a critical review", *Plant Ecology* 171, pp.69-79

[16] Martinez P. (1993). Modélisation de la croissance et de l'architecture du pin d'Alep. Mémoire de D.E.A., Ecosystèmes continentaux, arides, méditerranéens et montagnards; Rapport d'Ingénieur Forestier, Spécialisation Recherche; ENGREF Nancy, Université des Sciences et Techniques de Saint-Jérome Marseille, Agence MTDA, 39 pp.

[17] Godin C., Caraglio, Y. (1998). "A multiscale model of plant topological structures", *Journal of Theoretical Biology*, 191, pp.1-46.

[18] Godin, C., Guédon, Y., Costes, E., Caraglio, Y. (1997). Measuring and analyzing plants with the AMAPmod software. *In*: *Plants to ecosystems - Advances in Computational Life Sciences*, 2nd International Symposium on Computer Challenges in Life Science. M.T. Michalewicz (ed.). CSIRO Australia, Melbourne, Australie, pp.53-84.

[19] Reffye, P. de, Elguero, E., Costes, E. (1991). Growth units construction in trees: a stochastic approach. *In: 9th Seminar of the Theoritical Biology School, Solignac (FRA) 21-23 Sept. 1989; Acta Biotheoretica,* 39(3-4), pp.325-342.

[20] Reffye, P. de, Dinouard, P., Barthélémy, D. (1991). Modélisation et simulation de l'architecture de l'Orme du Japon *Zelkova serrata* (Thunb.) Makino (Ulmaceae): la notion d'axe de référence. *In: C.R. 2ème Colloq. Int. sur l'Arbre, Montpellier (FRA), 9-14 Sept. 1990., Naturalia Monspeliensa, 1991, (n°hors-série)* , pp. 251-266.

[21] Barthélémy, D., Caraglio, Y., Costes, E. (1997). Architecture, gradients morphogénétiques et âge physiologique chez les végétaux. *In: Modélisation et Simulation de l'Architecture des Végétaux*.

J. Bouchon, P. de Reffye and D. Barthélémy (Eds). *Science Update*. INRA Editions, Paris, France, pp.89-136.
[22] Hallé F., Martin, R. (1968). Etude de la croissance rythmique chez *Hevea brasiliensis* Müll. Arg. (Euphorbiaceae - Crotonoïdées). *Adansonia*, série 2, 8, 4, pp.475-503.
[23] Hallé F., Oldeman, R.A.A. (1970). *Essai sur l'architecture et la dynamique de croissance des arbres tropicaux.* Masson, Paris; 178 p.
[24] Caraglio, Y., Barthélémy, D. (1997). Revue critique des termes relatifs à la croissance et à la ramification des tiges des végétaux vasculaires. *In: Modélisation et Simulation de l'Architecture des Végétaux*. J. Bouchon, de Reffye P. and D. Barthélémy (eds). *Science Update*. INRA Editions, Paris, France, pp.11-87.
[25] Nelson, R.M., Adkins,C.W. (1988) “A dimensionless correlation for the spread of wind-driven fires”. *Can. J. For. Res.* 18, pp.391-397.
[26] Albini, F.A. (1981). “A model for the wind-blown flame from a line fire”. *Combustion and flames*, 43, pp.155-174.
[27] Isik, F., Isik, K., Yildirim, T., Li,B. (2002). “Annual shoot growth components related to growth of *Pinus brutia”*. *Tree Physiology* 22, pp.51-58.
[28] Lopez-Serrano, F.R., Landete-Castillejos, T., Martinez-Millan, J. A., Cerro-Barja, D. (2000). “LAI estimation of natural pine forest using a non-standard sampling technique”, *Agric. For. Meteorol*, 101, pp.95-111.
[29] Stauffer, D. (1985). An introduction to percolation theory. *Taylor and Francis ED*. 75p.
[30] Catchpole, WR., Catchpole, E.A., Butler, B.W., Rothermel, R.C., Morris, C.A., Latham, D.J. (1998). “Rate of spread of free-burning fires in woody fuels in a wind tunnel. Combust”, *Science and Technology*, 131, pp.1-37.
[31] Pimont, F. (2004). Modifications de l'architecture du Chêne kermès (*Quercus coccifera*, L.) en fonction de l'environnement de croissance. *Rapport de DEA BEE. Université de Montpellier II*, 63pp.
[32] Hu, B.-G., de Reffye,P., Zhao, X., Yan, H.-P., Kang, M.-Z. (2003). GreenLab: a new methodology towards plant functional-structural model. *In* Hu B., Jaeger M. (Eds), *Plant growth modelling and applications* (PMA03), Proceedings of the 2003' International Symposium on Plant Growth Modeling, Simulation, Visualization and Their Applications, Beijing, Chine, 13-16 octobre 2003. Beijing: Tsinghua University Press, Springer, pp.21-35.
[33] Yan H.P., de Reffye, P., Pan, C.H., Hu, B.G. (2003). “Fast construction of plant architectural models based on substructure decomposition”, *Journal of Computer Science and Technology*, 18(6), pp.780-787.
[34] Godin C., Sinoquet, H. (2005). “Functional-Structural Plant modelling”. *New Phytologist*, 166(3), pp.705-708.