Alábame y es posible que no te crea. Critícame y es posible que no me gustes. Ignórame y es posible que no pueda perdonarte. Aliéntame y nunca te olvidaré.

William Arthur Ward

Chapter 5

The role of fuels in the resulting heterogeneity of fire severity in a Mediterranean large forest fire

Abstract

Large forest fires have become one of the major forest management concerns, due to their consequences at an environmental, social and economical level. These broad-scale disturbances are frequently heterogeneous in their effects across the landscape, due to variations in the factors that influence their final severity: topography, meteorology and fuels. Even though several authors have minimized the role of fuels under severe meteorological conditions, fuels represent the major interest from the point of view of forest management, because they are the only factor that can be modified by humans. The alteration of wildfire behavior through changes in the fuel complex has long be intended, and constitutes the goal of fuel management . While there exists quite a long list of landscape studies dealing with the role of fuels and their influence on fire severity patterns, less effort has concentrated on lower-scale forest properties, such as the age and size of the trees, density or fuel arrangement, in terms of fuel continuity. This study analyses these lower-scale properties in an area affected by a large fire in North-eastern Spain, where fire had a patchy dynamic, leaving a heterogeneous combination of fire severities. It tests if, under moderate weather conditions, the structural characteristics of our forest stands affected the resulting distribution of fire severity. The results of our analysis report that forest structure did affect the final severity of fire. Green surviving plots were mainly those with more mature characteristics: lower densities, lower percent of small trees (DBH between 5 and 10 cm), higher percents of dominant trees, and higher basal areas. Dominant trees in these green plots were characterized by higher heights, larger trunks, and higher crown projections. This trend was also confirmed by the results of the individual trees, which also indicated that dominant trees with higher sizes, were the ones that survived the most. Regarding the fuel arrangement of these plots, more mature plots were characterized by larger horizontal continuities. At a tree level, individual green trees were associated to larger vertical continuities -and larger crown proportions-, and lower horizontal continuities. A preliminary review of these results, under the optic of forest stand structure, suggests that the structure of these trees could be related to more irregular, uneven-aged forests. This study give clues for forest management, as it shows how fuel structure conditions fire behavior in a Mediterranean fire. This reaffirms the key role of preventive fuel treatments, as powerful tools to avoid fire ignition, and to difficult the advance of fire in case it develops.

Key words: fuels; fire severity; survival; large forest fires; structural forest characteristics.

INTRODUCTION

Large fires are one of the most important management problems in many regions of the world (Malingreau et al. 1985, Minnich and Chou 1997, Johnson et al. 1998, Piñol et al. 1998, Vélez 2000). These large fires are frequently characterized by severe ecological, economic and social effects (Moritz 1997, González-Cabán 2000, Retana et al. 2002), whose importance, at least partially, depends on the spatial heterogeneity of burn severities (Glitzenstein et al. 1995, Schimmel and Granström 1996). This resulting heterogeneous distribution of burn severities and islands of unburned vegetation created by fire is mainly determined by three major groups of variables (Rothermel 1983, Pyne 1984): topography (i.e. elevation, aspect, slope); meteorology (i.e. wind, temperature, fuel moisture); and fuels (i.e. stand structure, fuel arrangement, forest composition). From the point of view of forest management, the greatest interest focuses on fuels, because they are the only one of these factors that can be modified by humans. The modification of wildfire behavior through changes in the fuel complex has long be intended, and constitutes the goal of fuel management (Agee et al. 2000, Finney 2001).

There is a reasonable consensus in the literature about the importance of fuels on the final heterogeneity of burn severities when meteorological conditions are not extreme (Williams and Rothermel 1992, Turner and Romme 1994, Kushla and Ripple 1997, Turner et al. 1997, Agee et al. 2000, Finney 2001). However, authors differ about the importance of fuels on fire severity under severe weather episodes. This disagreement has led to the establishment of two alternative hypotheses (see reviews in Bessie and Johnson 1995, Agee 1997, Cumming 2001): the weather and the fuel hypotheses. The weather hypothesis states that large severe fires are driven by extreme weather events and burn intensely through forests regardless of the condition of their fuels. The fuel hypothesis states that the spatial variations in fuels influence fire spread or severity, even under severe meteorological episodes. These hypotheses were originally established for western North American forests, but the dilemma has been extended to other forest ecosystems under other topics. Thus, Minnich and Bahre (1995), Minnich and Chou (1997), and Minnich (2001) defend, for Chaparral ecosystems, that the non-random turnover of fire patches, the structure of the landscape in areas with and without fire suppression policies, and the relatively few fires that develop into large fires, are related to characteristics of the fuels and stand-age. On the contrary, Johnson et al. (2001) and Keeley and Fotheringham (2001) defend that in closed canopy ecosystems, such as boreal forests or chaparral, large fires are weather-driven phenomena, not dependent on stand-age. They report that the idea of large fires associated to enhanced fuel build-up is not applicable to those ecosystems where fire suppression policies have not resulted in a reduced number of ignitions.

Different studies dealing with the role of fuels and their influence on fire severity patterns, rise the importance of landscape aspects such as: i) the degree of fragmentation or connectivity of the landscape, which determines whether fire spread is constrained by the spatial pattern of the patches and the number of ignitions (Turner and Romme 1994); ii) the spatial arrangement of forest stands (Finney 2001), which can act as natural fuel breaks or, contrarily, enhance the rates of spread; or iii) the proportion of patches of different species composition in the landscape, which directly relate to flammability properties of fuels (Cumming

2001). However, few studies have focused on lower-scale forest structure properties, such as the age and size of trees, density, and fuel homogeneity, on fire behavior (Turner and Romme 1994, Glitzenstein et al. 1995, Chappel and Agee 1996, Kushla and Ripple 1997, Turner et al. 1999). In these studies, certain consensus exists on the importance of some variables, such as tree size, on tree survival, while less agreement exists on other variables, such as the successional stage of the forest, probably due to differences in the ecosystems under study. This might explain why the main controversies about the effects of forest management on fire severity (e.g. even-aged versus uneven-aged structures, or species arrangement at the stand scale), remain in a qualitative, theoretical level, but few quantitative data are available to the decision makers.

In the Mediterranean basin, fuel management has a particular importance, due to the severity of fire episodes (Vélez 2000), the inflammability and combustibility of fuels (Pereira et al. 1995, Dimitrakopoulos & Panov 2001) and the hardness of climate (Delabraze 1986, Mérida 2000). This study focuses on the role of fuel structure in the variations of fire severity in an area affected by a large fire that occurred in the western Mediterranean area (Catalonia, NE Spain) in 1998. The objective is to test if the structural characteristics of forest stands affected the pattern of fire severities, in areas with similar topographic and weather conditions during the fire. To minimize external factors (i.e. meteorological conditions or topography) that could influence the resulting pattern of fire severities, homogeneous slopes without topographic disruptions or land cover changes were selected, and extensive field work was carried out to analyze the relationship between forest structure and fire severity.

MATERIAL AND METHODS

STUDY AREA

This study was performed in a large forest fire occurred in 1998 in El Solsonès county (Lleida, North-Eastern Spain, between 41º 59‘ and 41º 44‘ North and 1º 21‘ and 1º 39’ East) (Figure 1). Fire started in two consecutive days (18th and 19th of July) as two separate fronts. These individual fires combined into one large front (25 km), which was favoured by the extreme climatic conditions (warm and dry wind). Fire was finally extinguished on the 21st of July, affecting a final extension of ca. 26000 ha. The resulting burned land was characterized by areas of high spatial heterogeneity in the distribution of burn severities. Regarding the Forestry Inventory data (IEFC), among the 16033 hectares of forested land affected, 88% corresponded to woods (IEFC 2000). The primary forest species affected included *Pinus nigra* (74%), *Pinus halepensis* (11%), *Quercus faginea* (7%) and *Quercus ilex* (3%) (González & Castellnou 1998). A revision of data collected within the burned area by the Ecological Forest Inventory of Catalonia (IEFC 2000) indicated that 65% of the stations had small, dominated trees (individuals< 15 cm DBH), understory percents between 0-10%, and mean tree height for the dominant trees between 8-13 m. Non-forested areas (7853 ha) were mainly represented by croplands. Regarding the climatic characteristics of the area, 69% of the fire land has 100-200 mm of hydric deficit (Thornthwaite classification, WWW1). Annual rainfall within the burned area is approximately 650-700 mm, with a summer mean precipitation of 140 mm. Annual temperature is around

12ºC, with mean temperatures in the month of July around 21ºC (WWW1). Soils are mainly bright calcareous sandstones and loams.

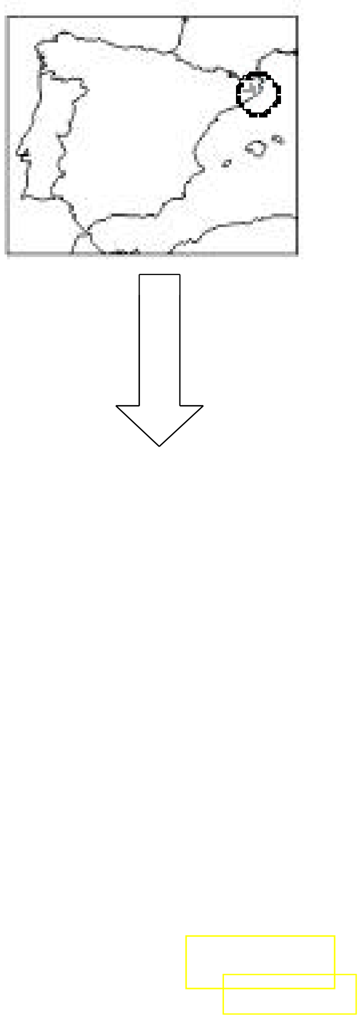

Figure 1: Location (in blue) of the large forest fire occurred in El Solsonés (northeastern Spain) in 1998, at a 1:125000 scale. The yellow box indicates the area where the two study zones were located.

Experimental design and sampling

Field data were collected during the months of March-July 1999. To concentrate on the role of forest structure and minimize the effect of external factors (i.e. meteorological conditions or topography), two zones separated by 4 km were selected in the burned area. Total areas of these zones were ca. 60 ha and 45 ha. They had similar topographical features (elevation of 700-750 m above the sea level, northern aspect and slope below 25º), lithological type (calcareous sandstones in both cases), and pre-fire forest composition (*P. nigra* was the main forest species in both areas; Forest Ecological Inventory of Catalonia 1993). Caution was paid to select zones where landscape elements did not affect fire advance (i.e. no abrupt slope changes, no fields in the middle of the slope). Selected slopes included the presence of three types of severities, similar to those described in Turner et al. (1994): i) charred areas: charcoal transformed stands or trees, with branches of different diameters left; ii) green surviving areas: stands with trees with a minimum of 45% of alive crown; and iii) mixed-severity areas: fire presented a patchy dynamics in these areas, resulting in a combination of burn severities, with charred, green and toasted stands-trees. Toasted trees were those affected by radiant heat, still holding their dried needles in the tree).

In each zone, 25 circular plots of 7.5-m radius were randomly selected for each severity, following a stratified random design. Due to the smaller size of the mixed areas, only 19 plots were carried out for this category in each zone. Sampling also included plots in patches of a given severity within a matrix of another severity (i.e. green surviving stands inside a homogeneous matrix of charred severity, or vice versa), in order to detect differences in forest structure between the patch and the surrounding matrix. The numbers of patches sampled were the following: six green patches inside the charred area in each zone, seven toasted patches inside the charred area in zone 2, and six charred patches inside the green area in zone 1.

In each plot, the total number of trees (with diameter at breadth height -DBH- larger than 5cm) and their DBH values were measured, in order to obtain total density and basal area per plot. Twenty-five trees were randomly chosen per plot. When the number of trees per plot did not reach 25, outer concentric trees were randomly selected. For each tree, the species, burn severity (categorical: charred, green or toasted), and vertical layer (categorical) were determined. The vertical layer was established dividing the maximum height of the trees in the plot in three levels: dominant trees were those reaching the tallest level, intermediate trees reached the height of the second layer, and dominated trees were located in the lower level. Total height and height to the crown base were measured for each tree. The percent of crown of each tree was computed from these two variables. When the crowns displayed different severities, their heights till each severity were also collected, so that the percent of crown affected by different severities could be calculated. Crown projection of each tree was also obtained as the ellipse of two perpendicular diameters of the crown.

To test the importance of fuel continuity, horizontal and vertical continuity indices were created following several steps:

i) the crown of each tree was divided into 8 directions, separated by angles of 45º.

ii) for each direction, the distances from the end of the crown of each selected tree, to the nearest crown in its same vertical layer and in the lower vertical layers, were measured. Thus, for dominant trees, these horizontal measures were calculated a) for the nearest dominant trees, b) for the nearest intermediate trees and c) the nearest dominated trees. Distances were limited to a range between 0 cm (contact) to a maximum value of 200 cm (no continuity). These thresholds (0-200 cm) were selected from the perspective of fuels, not from the perspective of fire.

iii) the Horizontal Continuity Index (HCI) was calculated as the sum of the distances in the eight directions to the same vertical layer (0: contact at 0 cm in all eight directions; 1600: no contact at 200 cm in any direction). The inverse values were used, so that the highest value (1600) indicated the maximum fuel continuity while the lowest (0) indicated isolation.

iv) the Vertical Continuity Index (VCI) was calculated as the sum of horizontal distances to the one-two lower vertical levels (i.e. for a dominant tree, distances to surrounding intermediate and dominated trees). Again, the inverse values were used; thus, for dominant trees, this index ranged between 3200 (maximum continuity), and 0 (vertical isolation).

Mean values of the 25 trees sampled per plot were used to determine values at the plot level for the following variables: height, crown projection and DBH of dominant trees, horizontal continuity values for dominant and dominated trees, and the vertical continuity value for dominant trees.

Data analysis

To test the importance of forest structure in the landscape distribution of fire severity, analyses were carried out at the plot and the tree levels. At the plot level, these analyses looked for differences i) among general severities defined in each zone: charred plots, green plots and mixed plots; and ii) among patches included into matrices of a different severity. The effects of SEVERITY, ZONE and their interaction were analysed by two-way ANOVA's over the selected structural variables of the plot: plot density, basal area, percent of basal area of conifers, height, crown projection and DBH of dominant trees, percent of dominant trees, percent of trees with DBH between 5-10 cm, percent of trees with DBH above 20 cm, horizontal continuity index for dominant and dominated trees, and the vertical continuity index for dominant trees. ANOVA's were calculated separately when considering plots of all severities for both zones, and when dealing with patches of a given severity included into a matrix of a different severity. When focusing on the structural differences between patches and their matrices, three analyses were made: i) green plots inside a charred matrix; this analysis included zone 1 and zone 2, as the same number of green patches were available in each zone; ii) toasted-trees patches included into a charred matrix, only for zone 2; iii) charred patches inside a green-unburned matrix, only for zone 1. In all cases, inspection of residuals was carried out to check for normality and homocedasticity. When necessary, analyses were run on transformed data. For all statistical tests, the sequential Bonferroni method was employed to control the group-wide type I error rate (Rice 1989). The individual values of the different levels of each variable were compared with a post-hoc test (Fisher's protected least significant difference).

As a further step to analyze the differences among plots in each severity, a principal component analysis (PCA) was performed. Plots of all severities of both zones, were included in this PCA. Using the information on the general distribution of variables offered by this PCA, a visual representation of plots of all severities was made. ANOVA's were performed to test for significant differences in the location of the plots of different severity (i.e., green, toasted and charred) along each of the first two PCA axes.

To analyze the role of the structural characteristics of individual trees, on the resulting fire severity affecting them, a second level of analyses was performed, focusing on individual trees. Variables included in this analysis were: tree height, crown proportion, DBH, crown projections and vertical and horizontal continuity indices. A PCA was performed only for dominant trees. Following the same scheme than in the plot section, ANOVA's were performed to test for significant differences in the location of the trees of different severity along the first PCA axes.

RESULTS

Structural differences among plots of different fire severities

Plots of different severities, without considering patches of a given severity immersed into a matrix of a different severity, displayed significant structural differences (Table 1). Structural variables whose response to fire severity was independent of zone were the density of trees in the plot, the basal area, the percent of trees with DBH between 5 and 10 cm, and the crown proportion. In these cases, green plots displayed lower densities of trees, lower percents of small trees (DBH between 5-10 cm), higher basal areas and higher crown proportions than the charred plots (Figure 2). The remaining significant variables were conditioned by ZONE due to structural differences between these zones (see interaction SEVERITY x ZONE in Table 1). Thus, zone 1 displayed higher percents of dominant trees (68.7±16 versus 57.9±15%), higher heights for the dominant trees (10.5±2.1 versus 9.0±1.5 m), higher basal areas (29±10.4 versus 23.2±7.9 $m^2.ha^{-1}$), higher horizontal continuities for the dominant trees (1185±216 versus 1109±226), and lower crown proportions (0.5±0.09 versus 0.6±0.09), than those of zone 2. According to the results shown in Figure 3, the patterns of this SEVERITY x ZONE interaction were similar for all significant variables (except the IHC): green plots of zone 1 displayed higher values than mixed or charred plots (Figure 3). In the case of the IHC, green plots displayed higher values than burned and mixed plots only in zone 2 (Figure 3E).

A principal component analysis (PCA) was performed at a plot level to revise trends among the considered structural variables (Figure 4). The first axis was responsible for 36% of the variance, while the second yielded another 19.6%. Variables distributed along the positive direction of the first axis include structural characteristics of the plots: height, DBH, percent of large trees (DBH>20cm), basal area, and crown projection (all of them referred to the dominant trees) (Figure 4A). In the opposite direction of this group of variables, for the first axis, it mainly appears the percent of trees with small diameters (5-10 cm). Variables related to fuel continuity are distributed along the second axis, with only the horizontal continuity playing an important role, while the importance of the vertical continuity is negligible in the first two axes. Basal area, plot density, and percent of dominant trees display similar trends to the horizontal continuity. The crown proportion displayed an opposite trend to the horizontal continuity. Considering this distribution of variables, several trends are observed when representing the plots of each zone (Figure 4B,C):

- In zone 1, plots of different severities were significantly separated along the first axis (F=35, d.f.=2, $p<0.0001$). Green plots display higher mean values (1.16±1.08) than mixed and charred plots (-0.05± 0.29 and -0.5±0.4, respectively), indicating that green plots are associated to dominant trees with larger heights, crown projections, and DBH's, together with a high percent of trees with DBH above 20 cm. The second axis did not display significant differences among severities (F=2.7, d.f.= 2, p=0.07). This indicates that the influence of fuel continuity (mainly the horizontal continuity), the density of trees, or the crown proportion, did not display a marked effect for the plots in this zone.

- In zone 2, none of the two first axes display significant differences among plots of different severities, (F=0.7, d.f.=2, p=0.5) for the first axis, and (F=1.2, d.f.=2, p=0.3) for the second axis.

Table 1: F values from the ANOVA tests of the effects of zone and severity on several structural variables at a plot level, for all severities. Significant coefficients (at _=0.05 when the sequential Bonferroni method is employed) are indicated in bold. Degrees of freedom: Severity, 2; Zone, 1; Severity x Zone, 2; Residual, 132.

Structural variables	*ZONE*	*SEVERITY*	*ZONE X SEVERITY*
Total density (trees ha^{-1})	2.0	**4.9**	2.0
Basal area (m^2 ha)	**8.2**	**12.4**	2.5
Percent of basal area of conifers (m^2 ha^{-1})	0.004	3.3	1.4
Height of dominant trees (m)	**4.6**	**19.4**	**17.7**
Crown projection of dominant trees (m^2)	3.3	**23.7**	**19.0**
Crown proportion (m.m^{-1})	**14.8**	**12.4**	1.7
Percent of dominant trees	**9.1**	0.84	3.9
Percent of trees with DBH between 5-10 cm	0.07	**7.5**	1.4
Percent of trees with DBH above 20 cm	3.3	**14.9**	**7.4**
DBH of dominant trees (cm)	0.6	**33.0**	**22.7**
IHC for dominant trees	**10.9**	2.9	**5.1**
IVC for dominant trees	1.3	1.9	2.8

Structural differences between patches of a given severity versus their matrices

The comparison of structural variables between green patches versus their charred matrices, shows that the results are independent of zone (Table 2). Green patches are characterized by taller dominant trees (10±1.0 versus 8.8±1.3 m), and lower percent of small trees (34.6±10.6 versus 47.1±13%) than the burned matrix. In the case of toasted patches inside a burned matrix (Table 3), toasted patches are characterized by lower tree densities (21.7±7.2 versus 31.5±10.8), lower horizontal continuities (793±210 versus 1097±213), higher heights for the dominant trees (10.6±2.1 versus 8.7±1.4 m), higher DBH's for the dominant trees (17.5±3.3 versus 14.3±2.8 cm) and higher crown proportions (0.6±0.07 versus 0.5±0.08). Contrary to what expected, the percent of dominant trees was lower in these toasted patches than in the burned matrix where they were included (46.5±11.8 versus 66±20) (Table 3). The comparison of burned patches included into a green matrix (only available for zone 1) indicates that burned patches display significant lower heights (F=15.7, d.f=1, p<0.0001), than the surrounding green plots (8.9±2.8 versus 12.5±1.8 m for burned and green plots, respectively). The rest of the variables did not display significant values.

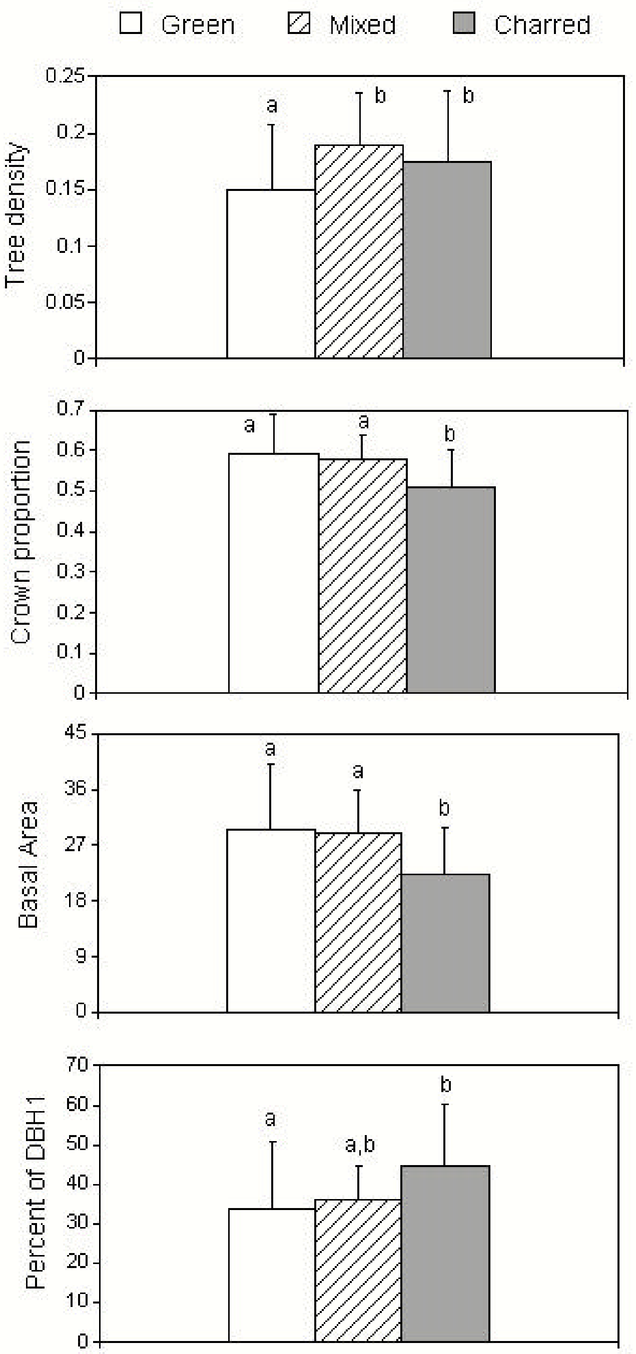

Figure 2: Mean ± standard deviation of the basal area ($m^2.ha^{-1}$), the density of trees ($num.m^2$), the crown proportion ($m.m^{-1}$), and the percent of small trees (DBH between 5 and 10 cm), for green, mixed and charred plots. Letters indicate significant differences among plot severities according to the Fisher PSLD post-hoc test.

Patterns of forest structure among trees burned with different severity

Concerning the structural characteristics of individual trees, the trends among variables obtained with a PCA are shown in Figure 5A. The first axis is responsible for 45.7% of the variance, while the second axis accounts for another 19%. Height, DBH and crown projections of the dominant trees determine the positive values of axis 1. Fuel continuity indices had a similar influence both in the first and second axes, displaying a marked opposite trend between them. For this tree level, the vertical continuity index, together with the proportion of tree crown, display a strong positive trend, while the participation of horizontal continuity was in the opposite direction. Considering this distribution of variables, several trends can be observed when representing all trees separated by zones (Figure 5, B,C):

- In zone 1, trees of different severities were significantly separated along the first axis (F=360, d.f.=2, p<0.0001). Green trees display the highest mean, being significantly different to the toasted and charred trees (0.74±1.0, -0.7±0.9, -0.19±0.8 for the green, toasted and burned respectively). Green trees are therefore associated to higher heights, DBHs and crown projections. For the second component (F=118, d.f.=2, p<0.0001), burned trees display the lowest mean (-0.5±0.8), significantly different to the toasted and green trees (0.5±0.9 and 0.04±1.1, respectively), that is, burned trees are characterized by lower vertical continuities, lower crown proportions and higher horizontal continuities than green/toasted individuals.
- In zone 2, trees with different severities displayed the same trends than those of zone 1, being significantly separated along both axes (F=57.4, d.f.=2, p<0.0001; F=17, d.f.=2, p<0.0001, respectively). Again, green trees are characterized by larger tree sizes, lower horizontal continuity and higher vertical continuity and crown proportions.

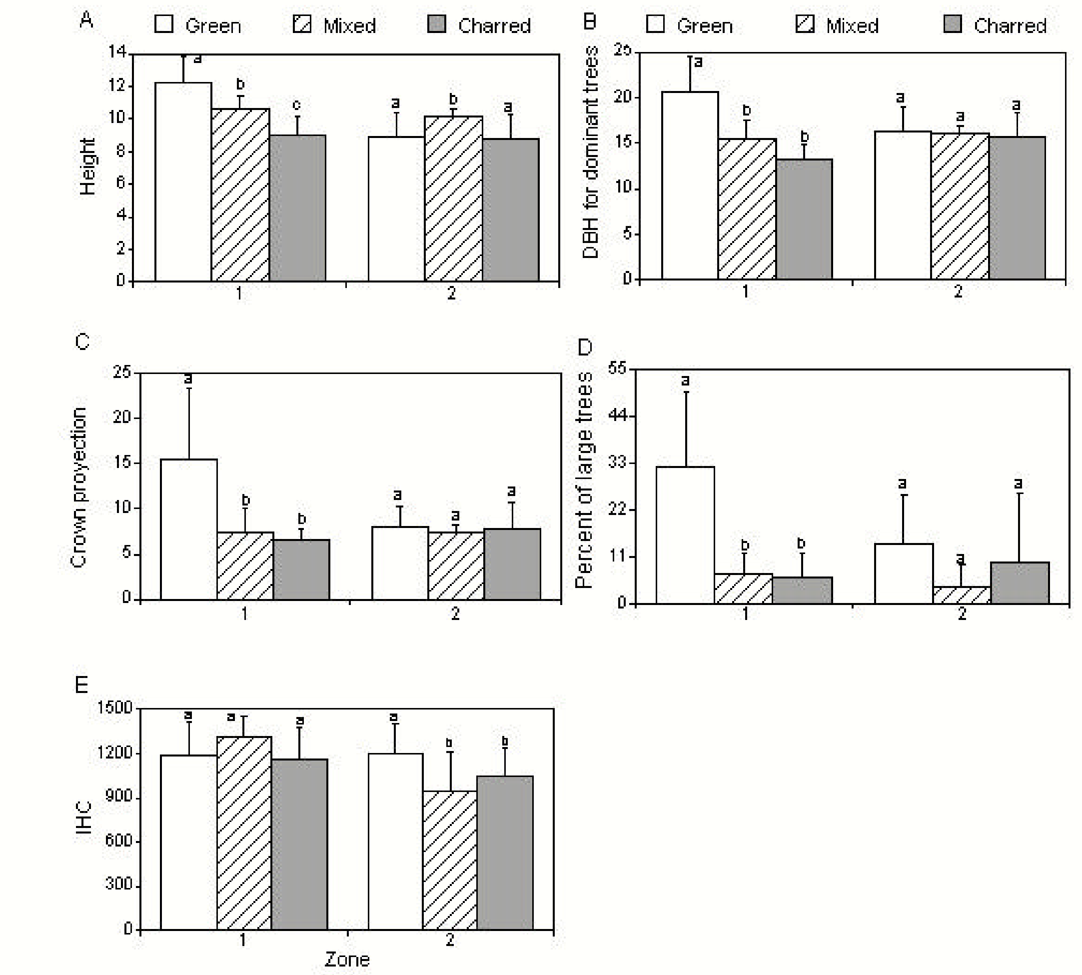

Figure 3*:* Mean ± standard deviation for those structural variables and fuel continuity variables whose response was conditioned by the interaction SEVERITY x ZONE. Letters indicate significant differences among severities according to the Fisher PSLD post-hoc test.

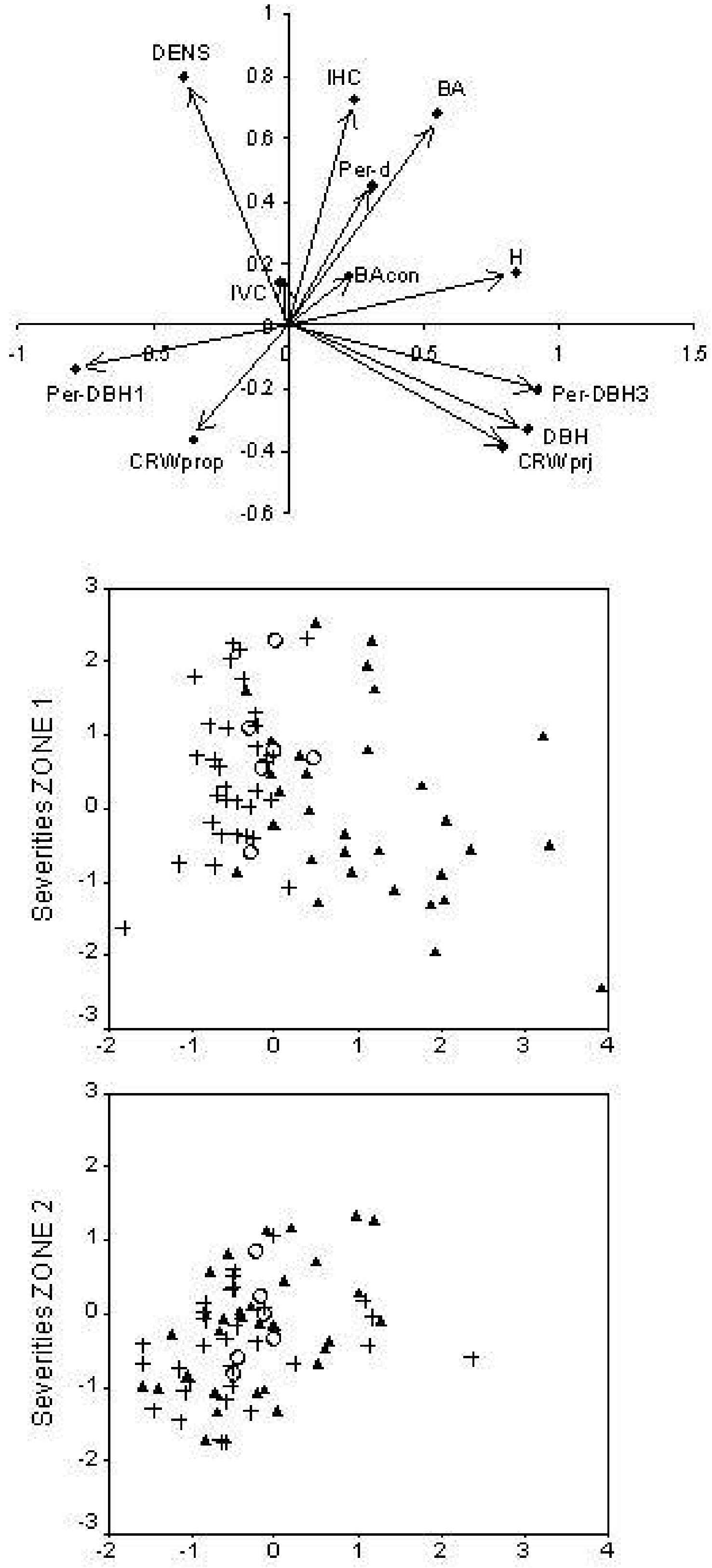

Figure 4: (A) ACP for the structural and fuel continuity variables considered at the plot level. BA: basal area; BAcon: percent of basal area of conifers; CRWprj: crown projections of dominant trees, CRWprop: crown proportion of dominant trees; DBH: diameter at breast height, DENS: density of trees; H: height of dominant trees; ICH: Index of Horizontal Continuity for dominant trees; IVC: Index of Vertical Continuity; PER-DBH3: percent of trees with DBH>20cm; PER-d: percent of dominant trees; PER-DBH1: percent of trees with DBH between 5 and 10 cm. (B,C) Severities of plots in Zone 1 and Zone 2 respectively, along the first two axes of the ACP.

Black triangles represent green plots, crosses represent charred plots and open circles represent toasted plots.

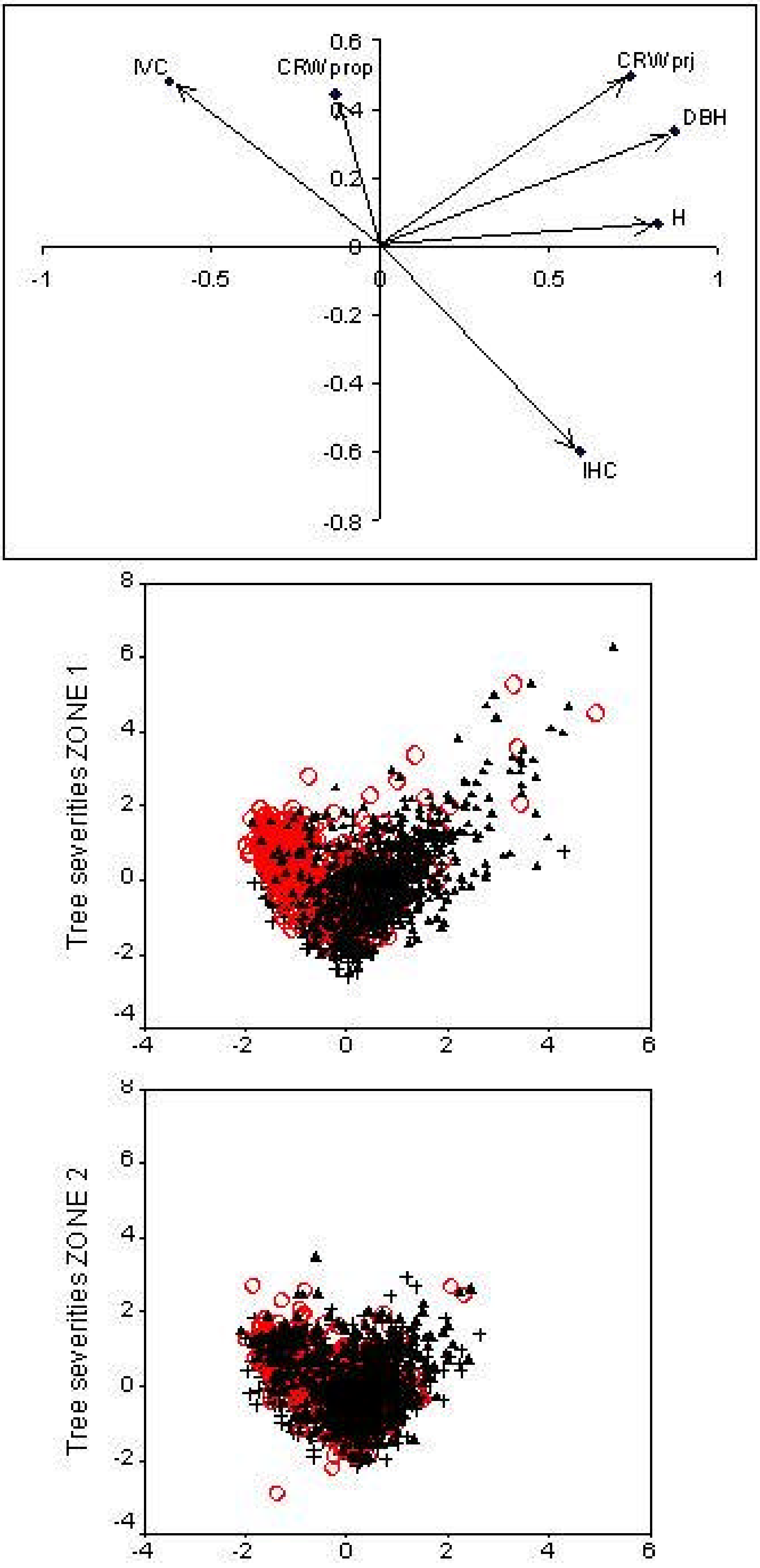

Figure 5: (A) ACP for the structural and fuel continuity variables considered at the tree level. DBH: diameter at breast height (cm); CRWprj: crown projection (m2); CRWprop: crown proportion; H: height (m), HCB: height to crown base; IHC: Index of Horizontal Continuity; IVC: Index Vertical Continuity. (B,C) Severities of trees in Zone 1 and Zone 2 respectively, along the axes of the ACP. Black triangles represent green plots, crosses represent charred plots and open circles represent toasted plots.

Table 2: F values from the ANOVA tests of the effects of zone and severity on several structural variables of the green patches versus their charred matrices, at a plot level. Significant coefficients (at _=0.05 when the sequential Bonferroni method is employed) are indicated in bold. Degrees of freedom: Severity, 1; Zone, 1; Severity x Zone, 1; Residual, 58.

Structural variables	ZONE	SEVERITY	ZONE x SEVERITY
Total density (trees ha^{-1})	3.9	0.07	0.04
Basal area (m^2 ha)	0.3	5.2	0.8
Percent of basal area of conifers (m^2 ha^{-1})	4.9	1.9	2.2
Height of dominant trees (m)	0.03	**10.6**	0.5
Crown projection of dominant trees (m^2)	0.05	0.29	6.1
Crown proportion (m.m^{-1})	**9.7**	4.2	4.0
Percent of dominant trees	1.5	0.1	7.5
Percent of trees with DBH between 5-10 cm	1.6	**8.6**	0.4
Percent of trees with DBH above 20 cm	0.5	0.6	0.3
DBH of dominant trees (cm)	**10.5**	6.3	0.15
IHC for dominant trees	0.1	5.6	0.4
IVC for dominant trees	**18.0**	3.2	0.2

Table 3: F values from the ANOVA tests of the effects of zone and severity on several structural variables of the toasted patches versus their charred matrices, at a plot level. Significant coefficients (at _=0.05 when the sequential Bonferroni method is employed) are indicated in bold. Degrees of freedom: Severity, 1; Zone, 1; Severity x Zone, 1; Residual, 56.

Structural variables	ZONE	SEVERITY	ZONE x SEVERITY
Total density (trees ha^{-1})	0.5	**7.6**	1.6
Basal area (m^2 ha)	0.02	3.9	2.2
Percent of basal area of conifers (m^2 ha^{-1})	0	0.1	0.4
Height of dominant trees (m)	1.7	**13.7**	0.8
Crown projection of dominant trees (m^2)	0.29	0.23	5.8
Crown proportion	**9.3**	**10.9**	2.2
Percent of dominant trees	5.9	**8.2**	0.8
Percent of trees with DBH between 5-10 cm	0.9	0.3	0.15
Percent of trees with DBH above 20 cm	1	1.1	0.008
DBH of dominant trees (cm)	7.7	**7.9**	0.015
IHC for dominant trees	0.005	**16.0**	0.7
IVC for dominant trees	**11.03**	2.4	0.14

DISCUSSION

Forest structure and fuel continuity influencing fire severity

The results of this study determine that, under moderate climatic conditions, forest structure, both in terms of tree sizes and fuel continuity, influence the distribution of fire severities. This influence is reported both among general severities in the slope, and also between patches of a given severity immersed in a matrix of a different severity (i.e. burned patches inside a green matrix). In our study, both green surviving plots and green trees, are mainly those with more mature characteristics -in terms of larger tree sizes- (larger DBH, higher heights, higher percents of trees with DBH>20cm, higher crown projections). Conversely, plots with high percents of dominated trees, lower heights and thinner trunks are more easily charred by fire. Studies dealing with forest pre-fire heterogeneity and its influence on the distribution of fire severity generally agree on the importance of larger sizes on tree survival (Turner et al. 1994,1999, Glitzenstein et al. 1995, Chappel and Agee 1996, Trabaud and Valina 1998, Agee et al. 2000, Finney 2001). It could then be hypothesized that more mature forests would be less affected by fire, and that any fuel management measure should accelerate the evolution of young forest stands, susceptible to fire, towards other stages, with lower susceptibilities to fire (Delabraze 1986). Studies performed by Glitzenstein et al. (1995), Chappel and Agee (1996), and Kushla and Ripple (1997) have also reported how old stands appear less susceptible to high-severity fire, while young stands burn more severely. Even though the obviousness of this statement, several studies have shown that older stands might burn more easily than younger ones. Thus, Turner et al. (1999) show a tendency of older successional stages to be affected by crown fire more than expected. Turner and Romme (1994) have also reported that fire burned intensely through 300-yr old forest stands but failed to be carried through the canopy when reaching 100-yr old stands. In the same line, Agee and Huff (1986) have reported an increased fire susceptibility on extreme successional stages: very young and very old forests burned more easily than intermediate age stages. The explanation given to this higher affectation of older stands relates to an increased fuel hazard linked to stand age, due to the development of a flammable conifer understory. These contrasting results indicate that more mature and older successional stages are not necessarily always less susceptible to fire, and that a revision of fuel evolution and fire susceptibility is required for each forest ecosystem under study.

Fuel continuity is another aspect linked to the structural characteristics of forest stands. In Mediterranean ecosystems, a continue fuel layer assures the existence of a heat source that pre-heats the surrounding fuels by radiant processes (Delabraze 1986). This is of major importance for the transmission of fire from ground to crown fuels, and it also favors the crown transmission of fire, specially in connected landscapes (Miller and Urban 2000). In our study, horizontal continuity of dominant trees plays an important role at the plot level. Larger horizontal continuities were associated to plots of larger sizes, with higher percents of dominant trees. This enlargement of the canopies, can be related to the fuel management of the area, that has favored higher DBH, higher heights and higher crown projections, by isolating larger trees by selective thinning processes, particularly in zone 1. The influence of the vertical distribution of fuels was less marked in the PCA analysis, not being associated to the structural characteristics of the plots (neither in size, nor in relation with the horizontal continuity). At the tree level, the horizontal continuity and vertical continuities played an important contrasted role. This last vertical index was associated to the proportion of tree crown. In this line, even though large crowns can help fire move along the crown, they may also have the opposite effect, under certain conditions. Thus, large crowns may act as a heat screen, favoring the survival of the upper parts of the crown. Regarding the structural characteristics of the trees and the forest structure, traditional silviculture relates larger tree crown proportions to more irregular stands (Oliver and Larson 1990). This irregular forest structure could be supported by the high vertical continuities and lower horizontal continuities of the green surviving trees. However, the role forest structure in terms of even-aged, uneven-aged, mature-immature structures and their relationship with fire risk, is still an open debate (Van Wagner 1983, Delabraze 1985, Stocks 1987, 1989, Madrigal 1992). In this line, Stocks (1987,1989) revised fire behavior in mature and immature stands of jack pine forests. Mature stands were characterized by an open understory, well separated from the canopy, that avoided fuel vertical continuity. This contrasted with immature, even-aged stands, where natural thinning, dense stand conditions, and the vertical fuel continuity allowed crown fire development once a moderated rate of spread is achieved. In terms of even-aged versus uneven-aged stands, and contrarily to our results, several authors have reported a lower susceptibility to fire of even-aged forests (Delabraze 1986, Madrigal 1992, Turner and Romme 1994). These authors defend that even-aged forests are less susceptible to fire when they have large dominant trees, with large distance from the ground to the crown base and a closed canopy that makes difficult the establishment of a dominated understory. Delabraze (1986) considered the juxtaposition of eve-aged stands of different age classes as a strategy to reduce the flammability of the landscape as a whole.

Fuel management strategies

The structural characteristics displayed by our green plots (large trees, more or less isolated), would be the objective of *fuel reduction or fuel isolation* treatments (Pyne et al. 1996), which try to decrease fuel loads within stands, or to divide forests into patches separated on the landscape by firelines or fuelbreaks, where fire spread is restricted (Pyne et al. 1996). There exists a diversity of methods to obtain fuel-breaks, but the final objective will always be to alter surface fuels, increase the height to the base of the live crown, and to open the canopy, by removing trees (Agee et al. 2000). As mentioned by this last author, the compartmentalization of fires by fuelbreaks may help reducing fire sizes but generally will not reduce damage per unit areas burned outside of the fuelbreaks themselves. Fuelbreaks were never designed to stop fires but to allow suppression forces a higher probability of successfully attacking a wildland fire. In our study, more open stands performed well as shaded fuel-breaks, as fire did change its behavior when reaching these areas. This was especially remarkable in the case of green patches of a given severity included into a charred matrix, where dominant trees were characterized by larger height and diameter, and lower percent of dominated trees than the burned plots. The fact that this pattern was similar in the two zones of study, suggests that there exists a fuel trend that is above the local properties of the forest stands. This is of special interest considering that both zones displayed considerable structural differences. A similar trend was observable for burned patches immersed into a green matrix. Thus, stands with trees with lower height and diameter, and lower number of large trees were particularly affected by crown fires, only surviving those stands with larger sizes. A third fuel treatment to reduce fuel hazard would refer to *fuel conversion* (Pyne et al. 1996), which implies the reduction of fire spread rates by species shifts towards less flammable species, most frequently increasing the density of deciduous trees. In our study, the percent of basal area corresponding to broadleaves was intended to measure the variability of broadleaves versus conifer species, in the stands. However, this variable was not significant, probably due to the low percent of broadleaves per plot.

If trees affected by lightings are the basis of the fires in the North-American old forests, dead, dry fuels, and large fuel continuities, are the basis for Mediterranean fires (Delabraze 1986). The continuity of ligneous fuels, the abundance of very flammable shrubs, a vegetation close to the withering point in summer months, dried soil surfaces, strong winds, a steep topography, and changes in socio-economic and lifestyles, have combined to worsen fire seasons in Mediterranean areas (Naveh et al. 1975, Delabraze 1986, Vélez 2000). Under these severe conditions, the role of fuels needs of further revision, as preventive fuel treatments are a powerful tool to avoid fire ignition, and to difficult the advance of fire in the case it develops (Velez 1990). This study shows that fuel structure may condition fire behavior in a Mediterranean large forest fire. That is, under moderate climatic conditions, the fuel complex influences the establishment of a heterogeneous distribution of burn severities. Altering the fuel complex should therefore be the objective of any forest manager that intends to protect the landscape against fire episodes. To cope with this objective, there exists a wide range of understory and overstory prescriptions and methods to modify fuels through manual and mechanical techniques, or prescribed fire (Agee et al. 2000). Among the potentials and limitations of each strategy to alter the fuel complex, manual and mechanical techniques are limited by their costs. Thus, fuel reduction and fuel isolation treatments by these means are only reasonable for small areas, but unaffordable for larger areas (Finney 2001). When prescribed burning is selected as the method to reduce and isolate fuels, costs are diminished, but a few aspects need to be considered (Johnson and Miyanishi 1995): i) the resilience of the affected communities and their habituality to the presence of fire; thus, as mentioned by Keeley and Fortheringham (2001) for the Californian chaparral, high fire frequencies, often caused by prescription burning, can pose an extinction risk to many species; and ii) the historical role of fire, to determine the extent to which prescription burning is needed for maintaining fire-dependent communities (Keeley and Fortheringham 2001). This creates the need to re-educate the public opinion about the goodness of certain types of fires, and to find an equilibrium between the benefits and prejudices of this ecosystem management.

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GENERAL CONCLUSIONS

1. Fire regime in Chiapas is characterized by a large number of small fires (80 % of the incidences are fires between 1 and 250 ha). However, these small fires are only responsible for a reduced percent of the total burned area (22%). Large forest fires play, therefore, an important role in the ecology of Chiapas' forests (8% of the incidences and 62% of the area burned in fires larger than 500 ha). Some municipalities have been particularly affected by these large fires, suffering from 32 large forest fires in the period 1993-1999 (Villacorzo). Most of these large fires are, however, surface fires of low intensities (80% of the incidences and 60% of the total area), that mainly affect non-forested land (shrubs and herbaceous layers).
2. The problem of fire in Chiapas is framed by several structural causes that include: i) a marked seasonal distribution of rainfall, ii) a habitual use of fire in traditional land activities and a lack of real alternatives, iii) a marked sensitivity to the presence of ENSO episodes, specially concentrated in rainforests, iv) a land tenure distribution that displays remarkable pressure on national lands, and v) particular flammability characteristics of its forests that concentrates fire in pine-oak ecosystems under non-ENSO conditions. Among the immediate causality, negligence and deliberate burning are the major causes of Chiapas' fires.
3. Factors that influence fire trends in Chiapas, under ENSO and non-ENSO conditions, reveal that there is an interesting shift in the major group of variables that determines fire trends, depending on the climatic conditions: environmental variables are the major factors determining fire trends in non-ENSO years while human variables are the major factors in ENSO years. Thus, in non-El Niño years, the status of the vegetation is the main cause determining fire ignition and fire spread in these years, while in the El Niño period, fire trends are mainly determined by the presence of ignition agents.
4. Altitude, pine-oak communities and poverty levels played major roles in the arboreal fire incidence in non-El Niño years, whereas the distribution of pastures appeared as an important variable determining arboreal fire incidence in El Niño years.
5. The main vegetation types affected by fire in non-El Niño years were the most flammable ones (i.e. pine-oak communities), while rain forests burned the most in El Niño years. The results of this study strength the importance of El Niño years in the conservation of rain forest ecosystems and suggest the existence of synergistic effects between fires, fragmentation and certain elements of the landscape, such as cattle pastures, in tropical areas.
6. The results of the methodological revision of remote sensing techniques that better characterize burned land, and better improve post-fire assessments, indicate that time consuming and expensive methodologies are not necessarily the most accurate, especially when potentially easily distinguishable classes are involved. Since no image processing technique was applied to the Raw Reflectance Data, it can be considered the most cost-effective methodology, whose importance was reinforced by the tree classifier.
7. When non-pure classes are included into the classification process, spectral noise is enhanced, and the overall accuracy decreases, offering an unacceptably low value. This noise is related to limitations in the pre-classification process related to the experimental design and the difficulty to characterize a common

non-pure class, both for the field survey and the satellite images.

8. For the classification procedure, three major limitations were detected for the image processing techniques: i) the use of a maximum likelihood classifier, ii) the presence of a strong dark background, and iii) technical constraints of some methodologies (i.e. the edge phenomenon in texture, atmospherical and soil noise in vegetation indices, and endmember selection and spectral ambiguity in SMA).
9. The revision of those factors that influence the survival of green islands within a fire indicate that the distribution of these unburned patches was not random. Conversely, vegetation islands were frequently located on large slopes, in areas with large amounts of forests, north and western aspects, with more mature forests (higher volumes of wood), lower infrastructures and lower diversities. The size of these islands was conditioned by the percent of forests, the size of the slope, the level of infrastructures and the volume of wood.
10. Landscape fragmentation was negatively related with island formation, in a way that, there were less islands in slopes with higher infrastructures and higher landscape diversities. For this reason, our results suggest that any fuel management strategy should avoid linear features (i.e. firelines and firebreaks), favoring any treatment that affects areas. The selection of these areas should take into account those factors that enhanced the creation of vegetation islands (i.e. larger slopes with more mature forests).
11. Structural characteristics of forest stands influenced the post-fire distribution of fire severity. Thus, under moderate climatic conditions, green surviving plots were mainly those with more mature characteristics: lower densities, lower percent of small trees (DBH between 5 and 10 cm), higher percents of dominant trees, and higher basal areas. Dominant trees in these green plots were characterized by higher heights, larger trunks, and higher crown projections. This trend was also confirmed by the results of the individual trees in plots of any severity, which also indicated that dominant trees with higher sizes, were the ones that survived the most. Any fuel management strategy should enhanced the evolution towards more mature conditions, as they better skip fire, under moderate climatic conditions.
12. Fuel arrangement is also a known variable that affects the post-fire distribution of severities in a burned landscape. In our plots, more mature stands were characterized by larger horizontal continuities, while individual trees displayed strong opposite trends between vertical and horizontal continuities, with green trees displaying higher vertical continuities and lower horizontal continuities. This fuel continuity will condition the forest management strategies to minimize fuel hazard. Thus, in the frame of our study, any forest management that favoured the establishment of irregular forest stands would have been preferred to regular forest stands.