SPATIAL DISTRIBUTION OF THE POTENTIAL EFFECTS OF WILDFIRES UNDER THE INTERMEDIATE DISTURBANCE HYPOTHESIS IN A MEXICAN FOREST ECOSYSTEM

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1. INTRODUCTION

The level of disturbance of a fire is related to its intensity and frequency. Very frequent fires are, in general, of low intensity, while a fire of low frequency is, in general, of high intensity. In the second case the result is a great damage of the forest ecosystem (structure and functionality). While in the first case, in general the damage is low, and rather we could have a lot of beneficial effects. Such as the establishment of regeneration, increase of biodiversity, etc. Based on the above mentioned, we could have three general conditions in a forest: a) Not disturbed forest; b) Intermediate disturbed forest (high frequency and low intensity fire); and c) High disturbed forest (low frequency and high intensity fire).

According to the Intermediate Disturbance Hypothesis (IDH), we can find a bigger number of species, or conditions, in an area that has been perturbed by a fire of high frequency and low intensity, which represents a intermediate disturb. In the case of a forest disturbed by a high intensity fire, this could be obvious. However in the case of a not disturbed condition an explanations is necessary. When a forest ecosystem has not be affected by a fire, within a considerable period, few species start to dominate the ecosystems, which could affect not only the number of individuals per species, but also the number of species (with the corresponding alteration of the ecosystem processes). In general such dominant species do not tolerate fire very well, therefore the occurrence of fire avoid their increment. The result of this is a lower competence among species, and specific conditions (fertility, light, and space) for certain species.

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One of the problems to apply this theory in operational activities is the lack of thematic maps that represent the spatial distribution of the potential fire intensity levels, and fire frequency [fire regime]. Therefore, this paper presents one of the first attempts to define the spatial distribution of potential effects of wildfires under the IDH, based on the distribution of fire intensity levels, in a Mexican forest ecosystem.

2. METHODS

2.1. Study Area

The study area was a watershed located at 5 km to the west of Tapalpa town (Jalisco state), in the west-central region of México (Figure 1). This area is located within the 19° 56' and 19° 58' North latitude; 103° 47' and 103° 51 West longitude (Benavides, 1987).

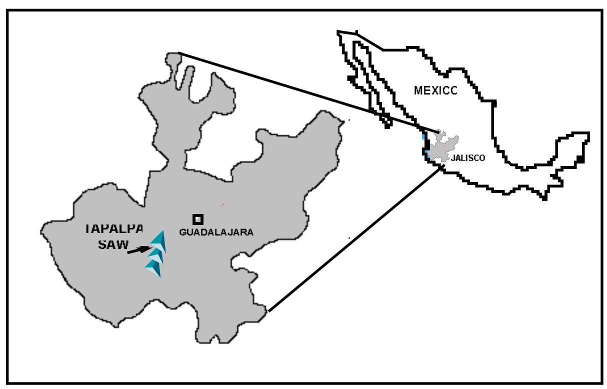


Figure 1. Approximate location of the Tapalpa Saw, in Jalisco, Mexico.

The Tapalpa Saw has the following general characteristics: *Altitude*: 1900-2400 m.a.s.l. *Mean annual rainfall*: 883.1 mm. *Mean temperature*: 16.6°C (*Minimum mean annual* 9.1°C, Maximum *mean annual* 24.3°C). This region corresponds to a temperate sub-humid climate (Benavides, 1987), and is dominated by *Pinus devoniana*, *Pinus* *oocarpa, Quercus spp, and Alnus spp*. The study area was mostly on north-facing slopes, at an altitude of 2110 m.a.s.l.. In average, the slope varied between 15 and 25%.

2.2. Data Collection

The information used in this study was collected based on a special forest inventory. Since we did not well the study area, we used a systematic sample design with sample plots located every 500 m, in an area of around 1400 ha. Both stand data (trees and environment) and fuel loading (1 hr, 10 hr, 100 hr, 1000 hr, shrubs, and saplings) were measured. A total of 79 600-m^2 circular sample plots were measured, during a period of 30 days (between May and June, 2003). Three concentric circular subplots of 200, 100 and 5 m^2, respectively, were also used (Figure 2). Forest fuels evaluation was based on the techniques and methodologies described by Brown *et al*. (1982). Plot center locations were determined using a global positioning system (GPS) receiver.

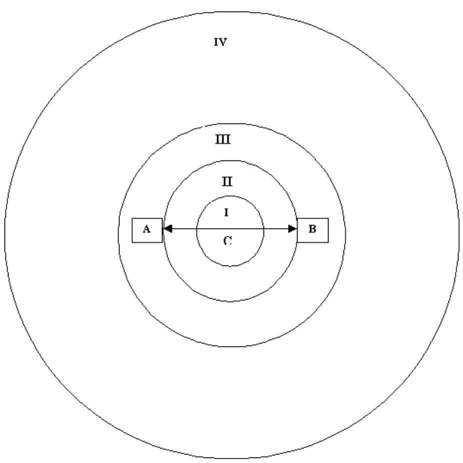


Figure 2. Concentric sample plots: ***A*** **and** ***B*** **for sampling fine fuels (litter and humus) [30 x 30 cm];** ***C*** **; Downed Woody of 0 - 7.5 cm of diameter (2 transects of 5.64 m, from the sample center to N and S directions, and a 11.28 m transect for downed woody > 7.5 cm of diameter.**

Circular sample plots of 1000 m^2 were used. In addition, each of these plots had three concentric circular subplots of 600, 200, 100, and 5 m^{2,} respectively, were used. The following site and forest stand data were collected within the 600 m^2 plots: a) tree species; b) diameter; c) height; d) crown height; and e) basal area; Shrubs were measured in the 200 m^2 circle; Saplings were measured within the 100-m^2 plots; while the information on natural regeneration was collected within the 5-m^2 sample plots. Fuels were inventoried along three transects.

2.3. Data Analysis

The analysis of information was divided into two phases: I) Defining of fuel thematic maps: and II) Location of areas according to their potential fire effect. For the former, two spatial interpolation analyses were tested to get five thematic maps: (a) 1-HR fuels; (b) 10-HR fuels; (c) Downed woody; (d) Fine fuels weight; and (e) Fine fuels depth. The used techniques were: ***(A) Inverse distance weighting (power 2).*** This technique assumes that the value of an unsampled point is a distance-weighted average of the values of observed points occurring nearby (Burrough and McDonnell, 1998). This interpolation technique gives more weight to closer observations than those that are farther away (Hunner, 2000). Such weights are inversely proportional to the distance between the point to be predicted and the data of nearby points computed, and are computed from a linear function (Burrough and McDonnell, 1998; Isaak and Srivastava, 1989):

$$\hat{\beta}^*(x_0) = \frac{\sum_{i=1}^{n} \frac{1}{d_i^p} * \beta(x_i)}{\sum_{i=1}^{n} \frac{1}{d_i^p}}$$

where: $\hat{\beta}$ ***$^*(x_0)$*** = estimated value at unsampled location x_0; β ***(x_i)*** = observed value at location x_i; ***d_i*** = are the distances from each observed locations to the unsampled point; ***p*** = distance exponent; ***n*** = number of sampled points.

(B) Ordinary kriging. OK is considered as the “best linear unbiased estimator” (Hunner, 2000; Isaaks and Srivastava, 1989): (a) Linear, because its estimates are weighted linear combinations of the available data; (b) Unbiased, because it tends to generate a mean square error equal to zero (E[Estimated(x_0)-True(x_0)] = 0, and $E\lambda_i = 0$); and (c) Best, because it aims at minimizing the variance of the errors (E{[Estimated(x_0) – True(x_0)]^2 = minimum). The following formulas are used to calculate the OK estimates (Hunner, 2000; Isaaks and Srivastava, 1989):

$$\hat{\rho}_{OK}(x_0) = \sum_{i=1}^{n} \lambda_i \cdot \rho(x_i)$$

where: $\hat{\rho}_{OK}(x_0)$ = ordinary kriging estimate at location $\boldsymbol{x_0}$; λ_i = the weight for sample point $\boldsymbol{i}$ at location $\boldsymbol{x_i}$; ρ $(\boldsymbol{x_i})$ = the value of the observed variable ρ at location ***xi.*** All the geostatistic estimations were defined under the assumption of an isotropic behavior of the data (omnidirectional approach).

To evaluate and select the interpolation techniques, cross-validation was applied. Cross-validation was also applied to find the optimal number of nearest neighbors to include in the kriging processes. The lower MSE was the criterion to select the best interpolation techniques (Flores, 2001).

The second phase of this study was based on the range of each fuel class (represented by the corresponding thematic maps) that could define certain level of fire intensity. Table 1 illustrates the potential of fire intensity that is defined according to a certain fuel classes conditions. The range values showed on this table were assumed according to the observed fire behavior occurred in the study area [under different scenarios].

Table 1. Ranges of fuel loads combinations corresponding to three fire intensity levels in the Tapalpa Saw, Mexico.

Fuel Class	High	Medium	Low
FF Weight	> 10	> 5	> 2
FF Depth	ANY	ANY	> 2
1-Hr	ANY	> 2	ANY
10-Hr	> 5	> 2	ANY
D. Woody	> 5	ANY	ANY

Each of these fire intensity levels were associated with the following three different potential scenarios: LOW= Not disturbed forest; MEDIUM= Intermediate disturbed forest (high frequency and low intensity fire); and HIGH= High disturbed forest (low frequency and high intensity fire).

3. RESULTS AND ANALISIS

One of the most frequent mistakes that are produced when one handles information, under a spatial approach, is that we put a lot of attention to get good field data, but we do not care enough to reflect the spatial distribution of such data the more accurately possible. Although there are several techniques to define the spatial distribution of a given variable, generally thematic maps are generated based on only traditional techniques (such as inverse distance weighting [IDW]). This does not mean that such techniques could no be useful, but it is important to compare them with other approaches. For example there are very few paper that report the use geostatistics techniques in forest fuel evaluation [i.e. ordinary kriging (OK] (Flores, 2001). Moreover, there only some papers that present a comparison of different interpolation techniques to define thematic fuel maps. In this case, both IDW and OK were compared in order to select the continuous surface that better represent the spatial distribution of each fuel class.

There is not a single interpolation technique that can be used in all the situation, therefore it was expected that not always OK would result in the better interpolation. However, one can decide to use OK based on the observation of the spatial autocorrelation of a given variable (Olea, 1991). The most used way to study such autocorrelation is through the variograms (Samra *et al.* 1989).

Figure 3 shows the variograms that correspond to each of the fuels variables. The exponential models was better to model most of these variables, except for the downed woody fuels. The latter showed also a not well defined spatial autocorrelation. Apparently, the rest of the fuel classes showed certain tendency of their spatial autocorrelation. Nevertheless in all the cases the nugget effect in highly marked, which represent a high variability among the values of close sample plots (Hunner, 2000). It is also important to point out that the corresponding sill is not well defined. This two conditions (nugget effect and sill) have defined that the models with the best fit have a horizontal tendency. Moreover, these models are too close to be represented by the general variance of the variable data. The variance value is reached at the sill level. On the other hand, the variogram models do not define well a horizontal tendency [after reach the sill]. Rather they tend to represent a higher and higher variance. In fact the resulted range values (the distance of separation between site pairs), where the sill is reached, were considerable high: from 3522.9 to 9110 m Theoretically, such tendency could be considered when an universal kriging process is used (Flores, 2001).

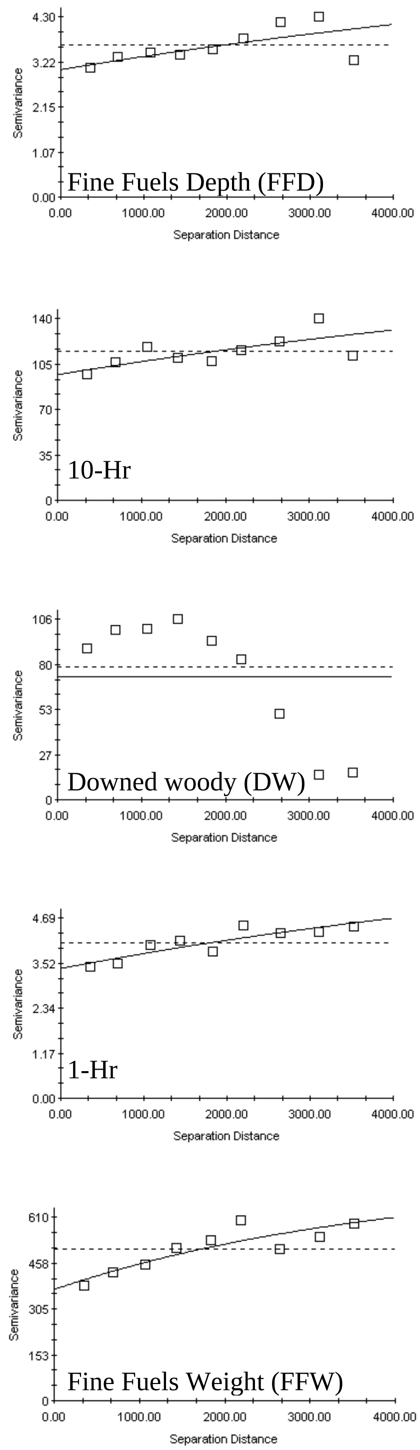


Figure 3. Variograms and the corresponding model of fuels variables: FFD, FFD, 1-Hr, and 10-Hr =Exponential; DW= Linear.

The analysis of the variograms resulted in the selection of the variogram models that better fit the spatial autocorrelation of each fuel variable. This would support the OK interpolation process. Comparing the observed values with the estimated ones, the corresponding MSE were computed.

The continuous surface for each fuel class were also generated using a IDW process, based on a power value of 2. After that , the corresponding MSE were calculated.

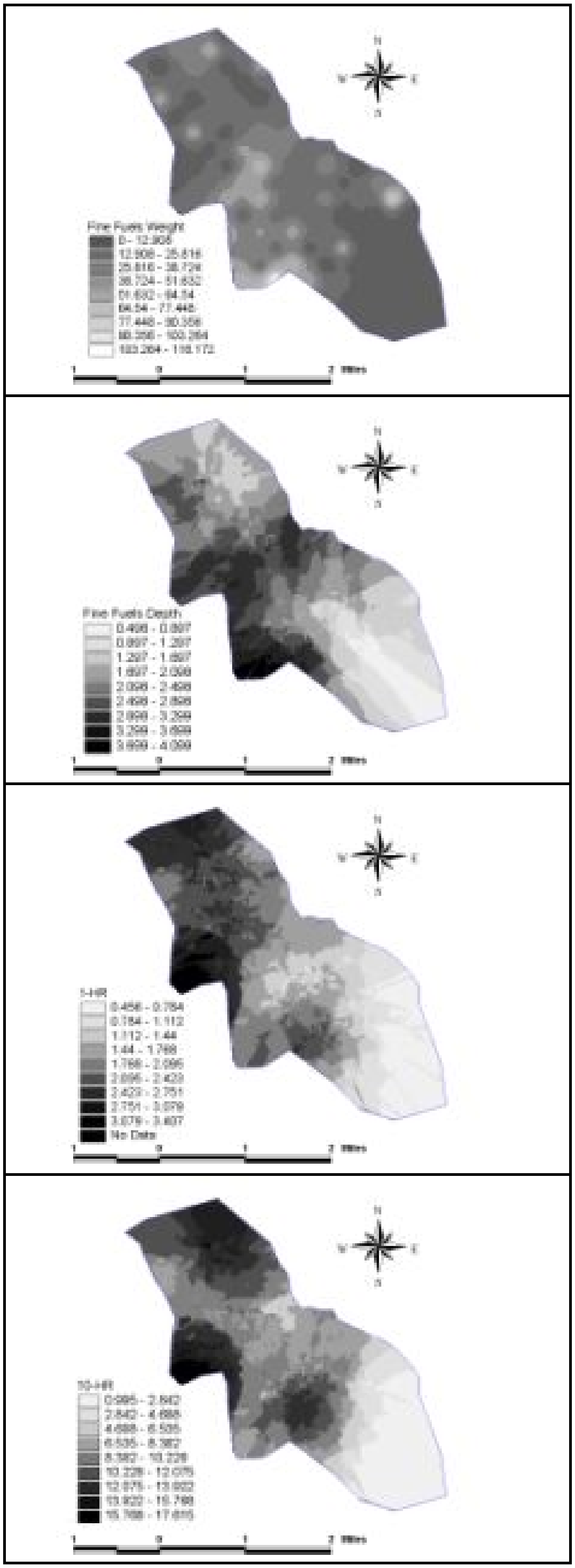
Once that all the continuous surfaces were defined, the next step was to select the ones that better represent the spatial continuity of each fuel class. As was mentioned, the lower MSE was used as the criterion of selection. Table 2 show the resulted MSE resulted from each interpolation technique. As it was expected, according to its low spatial autocorrelation, IDW defined a lower MSE than OK. Nevertheless, It was expected that, based on its similarity with the other variables, OK estimated better the values for fine fuels weight than IDW.

Table 2. Comparison of mean square errors between ordinary kriging (OK) and Inverse distance weighting (IDW).

VARIABLE	OK	IDW
Fine Fuels Weight	445.7507	445.0049
Fine Fuels Depth	3.702813	3.747062
1-Hr Fuels	3.66165	3.70085
10-Hr Fuels	113.5366	113.7293
Downy Woody	83.0.4424	81.22772

According to the above resulted, not always the interpretation of a variogram is enough to decide whether OK will result in the better estimation or not.

The last step, in the first phase, was to generated the thematic maps for each fuel class, which are represented in Figure 4. Where is notable the difference of the spatial distribution of fuel classes between OK and IDW. The latter tends to define a distribution where the values in the sample plots have a considerable weight. While in the case of OK such distribution is more homogeneous. This differences in spatial distribution could be associated to the distribution of other variables, such as tree diameter, tree density or tree diameter.



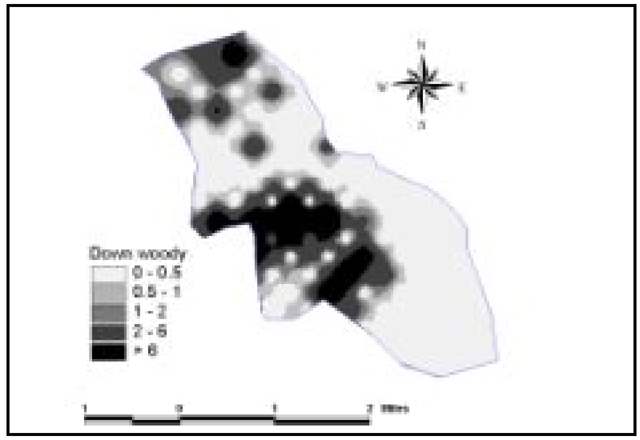


Figure 4. Continuous surfaces of forest fuel loads, corresponding to each fuel class. All the values are in tn/ha, except for fine fuels depth (cm).

Once the fuel maps were generated, it was possible to define the regions that correspond to the conditions established in Table 1. Figure 5 represents the spatial distribution of such conditions, where it is possible to appreciate that most of the watershed is classified as not disturbed forest, which correspond to a 41% of the total area. The low amount of fine fuels could make difficult both that a surface fire start, and that it spread out. This assumption is also supported by the fact that this area has to have a fine fuels depth of at least 2 cm. In this area could be possible to find some larger fuels (such as 1-hr and 10-hr), however the potential fire intensity can be considered low. This scenario could allow a continuity of the succession vegetation process. According to Arno (1980), fire "cuts" the vegetation succession cycle and lets fire-tolerant early successional forest vegetation remain in a specific site. Furthermore, Fuller, (1991) consider that if there are not fires in a given forest the natural vegetation succession will follow its cycle to later-succession, less fire-tolerant forms of vegetation, resulting in a change of biodiversity.

Eventhough a fire could occur in the low-intensity area, fire intensity could be too low that not-fire-adapted vegetation could support this kind of wildfire (Allen, 1996). According to the intermediate disturbance hypothesis, this kind of low perturbation will allow: a) changes on vegetation composition; b) fuel accumulation; and c) change of vegetation structure, mainly focused to small diameters. In general, when there is absence of fire (or if it is of very low intensity) fire-adapted plants tends to be displaced by a more tolerant species (basically shade tolerant). Eventually, this result in a low biodiversity (low number of species, represented by many individuals). It is important to point out, that in Mexico there are very few studies that can support these theories. However, the experience of several years from fire fighters and fire scientist allow to base such assumption. Also it is important to mention that the fuels loads combinations (Table 1) that define the distribution of a low intensity fire still need a lot of studies. However, the concept is acceptable, because fire intensity is strongly associated with fuel quantity and quality (Anderson, 1982).

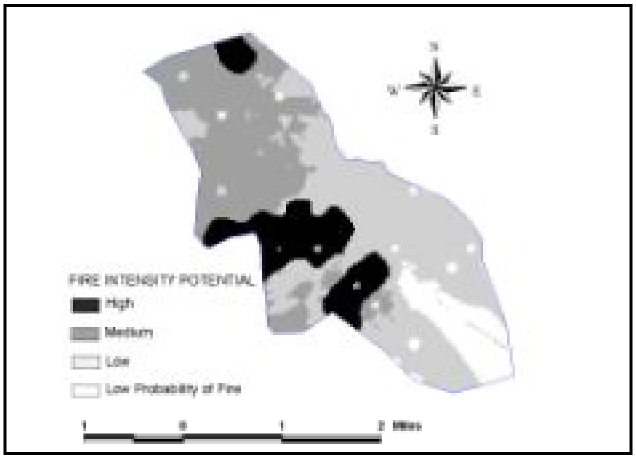


Figure 5. Thematic map of the spatial distribution of fire intensity in a forest stand of Tapalpa, Mexico.

Eventually, two possible future scenarios could take place in this low-intensity-area: 1] A fire could occur in the short time, which will return this area again to its original condition; 2] Because the absence of fire in a long period, fuels accumulation could produce a high disturbance. The latter situation take us to a potential high intensity condition. Which imply that the studies of the potential of fire intensity must be considered dynamic. Therefore, we must oversee the tendency of the spatial fuel distribution. This information is also important when we try to maintain a given condition, such as wildlife habitat or vegetation diversity.

On the other hand, 506 (36%) corresponded to a potential medium fire intensity, which could result in an intermediate disturbed forest (high frequency and low intensity fire). In this case fire play an important role to maintain forest biodiversity. Theoretically, as it was mentions, without fire the vegetation succession cycle would continue, with a tendency to decrease biodiversity. The reason of this that the new condition would be acceptable only for a few number of species (basically shade tolerant). Therefore, when a perturbation occurs, such cycle is cut or, in some cases, returned to earlier stages. This dynamic implies that the kind of vegetation, that exist in these medium-fire-intensity areas, should have certain level of fire tolerance or fire dependency. For example, Johnston (1971) and Smith (1986) suggest that some conifers which become established most readily on bare mineral soil, reproduce poorly because favorable seedbeds are covered by litter. Thus, eliminating or decreasing litter on the forest floor will result in better conditions for natural regeneration. Furthermore, De Bano (1976) and Wade (1989), suggest that through prescribed fire, nitrogen and other nutrients contained in dead vegetation, are released into the soil (mineralized), which results in an increase in soil fertility, which improves the seedbed. Nevertheless, it is important to point out that to get such results fire intensity must be between the following conditions: a) it has to be intense enough to be able to reduce the litter layer, but b) it has not to be to high in order to avoid the elimination of soil protection and the damage of vegetation. Knowing the spatial distribution of a potential medium-intensity-fire a forest manager could take decisions in order to implement prescribed fires (Fuller, 1991).

Since [theoretically] according to the intermediate disturbance theory we could expect a higher biodiversity in those forest with a not-intense-not-low perturbation, we could consider that a intermediate disturbance is required. Such disturbance has to be not necessarily produced by a fire, however I the study area fire is the main factor that alter forest ecosystems. Also we must consider that the dependence of some species, which define their presence in a given area. In these cases we must consider not only the fire resistance of some species, but also the fire dependence (specially regarding cone serotinity). Therefore, to be sure that we could have the enough fire intensity, we must have a precise knowledge of the spatial distribution of quality and quantity of fuel classes. We can not base our fire management strategies only on generalized estimation of spatial fuel distribution, such as fuel models. This is because fuels distribution could be highly heterogeneous, even in short distances. Therefore, the information that is presented in this paper is greatly useful, because we have a high level of certainty of the special changes of fuel distribution. Moreover, we can make some combination of the information of different fuel classes in order to define not only potential fire intensity, but also habitat conditions for wildlife.

Perhaps, the areas qualified with a potential high intensity fire (potentially high disturbed forest [low frequency and high intensity fire]).should be attended with priority. In this study, 11% of the watershed fall in such category. The intermediate disturbance theory considers that such areas tend to be dominated for few shade-tolerant species, displacing many species adapted to more open spaces. This situation could not represent a problem, but we must consider the social and economical approach of the study area: a) since the studied watershed is and important source of timber, it is necessary to maintain the environmental conditions that are favorable for the timber species. Which corresponds to a intermediate disturbance level; b) society is frequently interested to keep the current forest conditions (composition, structure, and density), which is not possible if the vegetation succession cycle has not any interruption. Therefore, fire (of intermediate intensity) represent an valuable alternative to modify the fuel distribution and quantity of the areas of potential high-intensity fire. Since, based on the methodology illustrated in this paper, we have information not only of the dimension of the problem, but also it location, we can make better pacification of the management of such areas. Moreover, we should consider not only the recreation and economical importance of this information, but also the support that can represent for the implementation of fire management strategies.

4. CONCLUSIONS

Fire affect not only many elements but also many processes of a ecosystem. The level of these impacts is related to the fire intensity and frequency. However, in many studies fire is considered as a constant factor without variations on time and space. As a result of this the corresponding conclusions are too general. For instance it is not well known how is the dynamics of plant establishment and growth after fire. These processes have to be related to the spatial distribution of fire characteristics, because the impact of fire vary according to its frequency and severity. The effects of a given fire on biodiversity are very different if we consider a fire of 300 Btu/ft^2 than one of 48,000 Btu/ft^2. Also it is important to relate regeneration with fire frequency. If a fire is very frequent could has different effects on plant establishment that a fire of low frequency. In general, it can be said that frequent, repeated fires would be likely to alter the structure of plant communities significantly (Williams *et al*. 1994).

Once that we know the spatial distribution of potential impacts of fire, we could define specific fire regimes, according to a desired biodiversity condition. On other words we have to define the adequate combination of intensities, frequencies and seasons of fire occurrence that produce certain environmental conditions, which are favorable for a specific biodiversity. As a result of this, it could be defined a systems of hazard reduction burns (of variable intensity and spatial distribution), and a fire-free intervals to maintain a certain biodiversity. However the probability of prescription depend of the knowledge of the effects of fire on biodiversity. Although in some case we can interpolate some effects in two areas, we have to evaluate the similarity of such areas. On the other hand, when we want to define biodiversity we have to consider not only the ecological aspects, but also the objectives of society.

Although fire frequency was not [directly] considered in this study, it is recommended to develop thematic maps that reflect the more accurate possible the spatial distribution of fire frequency. Which is strongly related to fuels presence.

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