

Sustainable Forest Management Support Based on the Spatial Distribution of Fuels for Fire Management

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Abstract—Fire behavior simulation is based mainly on the fuel model-concept. However, there are great difficulties to develop the corresponding maps, therefore it is suggested the generation of four fuel maps (1-hour, 10-hours, 100-hours and alive). These maps will allow a better definition of the spatial variation of forest fuels, even within a zone classified as a given fuel model. The used data was acquired under a forest inventory of 554 sample plots, within an area of 1,400 ha approximately, in the ejido El Largo y Anexos (Chihuahua, México). Twelve different interpolation techniques (five deterministic and seven stochastic) were used to generate continuous surface of each fuel class. These surfaces were evaluated and compared. In general, stochastic techniques produce the best results, although individually the technique called inverse distance weighted showed a more constant performance. It is suggested that there is not a single interpolation technique to be used for any variable. The generated information (fuel maps) would help to the decision making process for a sustainable management of a given area, because it would help implement fire management strategies.

Introduction

Sustainable forest management planning considers the function of many elements, of a forest ecosystem, but also their interrelations. Since it is difficult to evaluate the total number of element, decision makers must define which are the more important elements. In order to do this we must consider an integrated approach that guarantee, basically, forest regeneration. In this way, the elements that represent, of support, disturbance occurrence have a high priority. This hierarchy approach is useful when: a) it is difficult to know all the forest elements; b) it is difficult to measure the influence among elements; and c) there is a limited budget. Disturbance factor, such as pest, hurricanes, and fire, could affect forest sustainability in both a very short time period, and in very large areas. Among them, fire is more common in most of the Mexican forest ecosystem, affecting not only vegetation regeneration, but also trees and other biotic and physic elements. Therefore, any management planning (focused on sustainability) must consider: i) fire occurrence (frequency) and ii) fire intensity. The definition of such aspect can be supported with the use of fuel maps. However, the definition of the spatial distribution of fuel models has represented one of the more complicated challenges facing forest fire scientists (Keane and others 1999). As an alternative, the fuel-model concept (numerical

characterization of fuels [Rothermel 1972]) has been a practical solution for this problem. However, this concept consider fuels (quality and quantity) distribution homogeneous within an area qualified into a given fuel model. That means that fire behavior variation will be based only on changes of wind, fuel moisture, and slope (Omi 1997). However, the spatial distribution of forest fuels tends to be rather discontinuous and highly variable (Brown and Bevins 1986). Since most of the current fire behavior simulation models are based on the fuel-model concept, the objective of this study is to show an alternative approach in order to develop three dead fuels maps. This information will be useful to support sustainable forest management under Mexican forest ecosystems.

Methods

Study Area

This study was carried out with information on forests of the ejido “El Largo y Anexos”, located in the region called Mesa del Huracán, at the NW of Chihuahua State, México (fig. 1). The predominant tree species are *Pinus durangensis*, *P. arizonica* (Engelmann), *P. Engelmanni* (Carriere) and *Quercus sideroxyla* (Humb. and Bonpl.). A fuels inventory was carried out in 1998 where a total of 554 plots, randomly distributed, were sampled in a

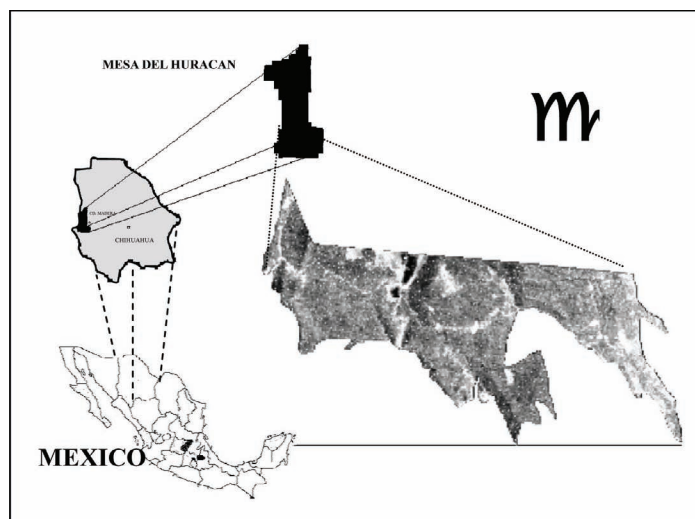


Figure 1. Approximate study area location, close to Cd. Madera (Chihuahua, México).

1400 ha area. Fuels loading (1 hr, 10 hr, 100 hr, shrubs, and saplings) were measured based on the techniques described by Brown and others (1982). Sample plots locations were determined using a global positioning system.

Fuel Map Generation

The three fuel loadings maps used in this study were generated by Flores (2001). Three are based on fuel timelag classes (Deemnig and others 1978), that is, a measure of the rate at which a specified size of dead fuel gains or loses moisture [i.e., 1-HR, 10-HR, and 100-HR fuel classes]. These maps were generated comparing five statistical interpolation methods (spline, polygonal mapping, inverse distance weighting [power 1 and 2]) and five geostatistical options (ordinary kriging [point kriging and block kriging], universal kriging [1st and 2nd degree], and cokriging,) (Flores 2001). Based on these techniques were defined the continuous surfaces that more accurately represent the spatial distribution of four fuel classes (tn/ha). Interpolations were based on field data.

The ancillary data required for cokriging were gathered from a Digital Elevation Model, a Landsat 5 TM and a forest inventory. The four fuel classes showed significant autocorrelation and cross-correlation, thus it was possible to model the spatial continuity of each of the four fuel types. The average spatial dissimilarity between data points defined a structural distribution (variogram), which allowed characterization of spatial continuity patterns (Flores 2001) and definition of weighting factors for both kriging and cokriging (Hunner and others 2000).

Results

Fuels Statistics

Fuel loadings (tn/ha) were related to the forest stand conditions where the evaluations were made. General statistics for the four fuel types are shown in table 1. The fuel class loadings were combined with the secondary variables selected from a stepwise process.

Fuels Interpolation

Using elevation (ELE) as secondary variable, and modeling such relation with an exponential cross-variogram, resulted in the lowest MSE for 1-HR, and 100-HR. However, other combinations resulted in similar results. In the case of 1-HR principal component 3 (PC3) (exponential cross-variogram) was the secondary variable that result in the lowest MSE. Table 2 summarizes the performance of all the 10 interpolation techniques used to estimate each fuel class loading. The evaluation of this performance was based on four measures: Mean square error (MSE). MSE ranges from 0.162 to 0.929, 2.157 to 4.385, and 39.84 to 183.37, for 1-HR, 10-HR, and 100-HR, respectively. These ranges represent a considerable difference among the interpolation techniques. In the cases of 1-HR and 100-HR fuels, the lower MSE was obtained through cokriging (CK) procedure based on elevation (ELE) as a secondary variable. This suggests an increase in precision when modeling the joint spatial continuity of fuel classes and ELE. By contrast, CK was the worst technique in the estimation of 10-HR fuels. In this case the lowest MSE was obtained through the inverse distance weighting (Power 1).

Fuels Continuous Surface

Based on the best interpolation techniques, the corresponding continuous surfaces were generated for each forest fuels (fig. 2). The spatial distribution of 1-HR fuels shows that higher loads are located at the west portion of the study area. The lower loads of this fuels occurred at the east, which could be explained because the minor tree

Table 1. General statistics of the four fuel classes for the study area (Cd. Madera, Chihuahua, México).

Statistic	1-hour	10-hours	100-hours
Minimum	0.08	0.00	0.00
1st Quantile	5.26	0.66	0.00
Mean	11.32	2.08	10.09
Median	10.34	1.31	7.22
3rd Quantile	16.30	2.63	14.45
Maximum	35.45	13.79	101.14
Std. Deviation	7.41	2.19	14.33

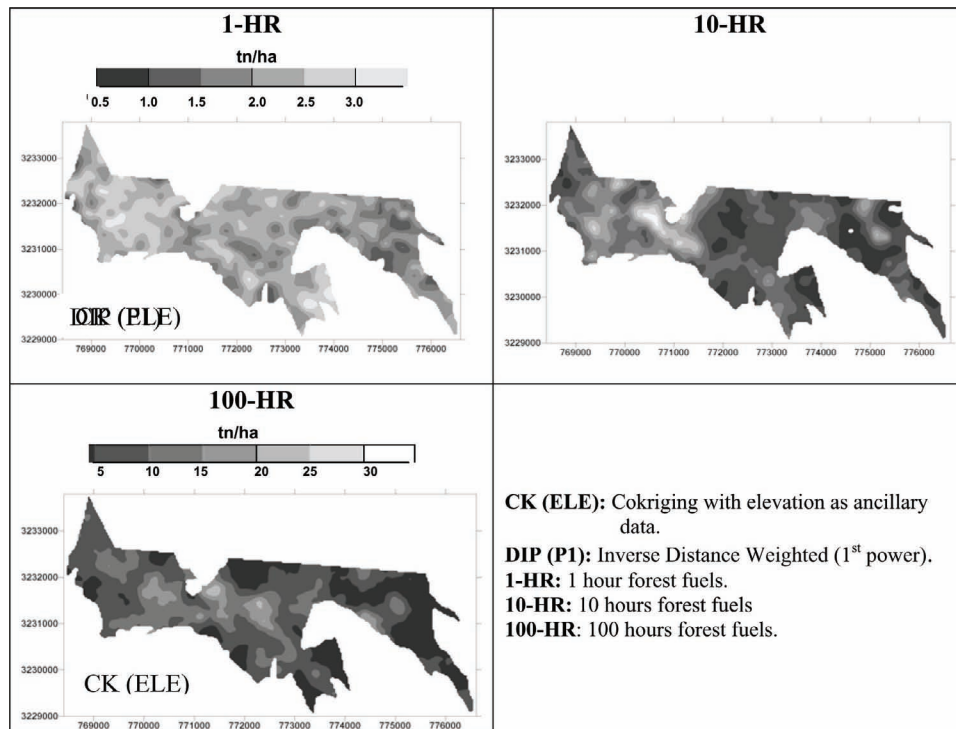


Figure 2. Thematic maps of three dead fuels spatial distribution for the study area located close to Cd. Madera Chihuahua, México (after Flores, 2001).

density. On the other hand, 10-HR fuels showed a more variable distribution, however higher loads are located at the east. Lower loads occurred at both central and east portions of the study area. In the case of 100-HR, fuels distribution is less heterogeneous and there is a clear tendency of low loads at the east portion. Higher load values are located at the central part of the studied area. In general, we could say that the reason of the low loads at the east part are because this portion is close to the Cd. Madera town. Since people from this town get firewood from the forest, it sounds logic that they take it from the closest areas. Therefore, any management planning should consider two kind of priorities: a) defining those areas with high risk of fire, which are related to their proximity to urban areas (Flores 2004); and b) considering the potential fire effects, based on fuel load-

ings. This means that forest managers not only should avoid fire occurrence (mainly in the areas close to the town), but also to implement silvicultural practice to decrease fuel loading (for example prescribed fires [Flores and Benavides 1993]).

Discussion and Conclusions

Geostatistical interpolation techniques showed a better performance than the traditional interpolation techniques tested (table 2) for the four fuel classes (1-HR, 10-HR, and 100HR fuels), in general. Similar response is reported in other studies (Hohn 1998; cited by Hunner 2000). The results suggested no increases in the precision of our

Table 2. Performance of the interpolation techniques evaluated by four measures, for each fuel class, for the study area (Cd. Madera, Chihuahua. México).

Fuel class	criteria	Statistical					Geostatistical				
		spline	polyg. mapping	thiessen	idw power 1	idw power 2	uk 1st degree	uk 2nd degree	cokriging (ele)	point kriging	block kriging
1-HR	MSE	60.846	33.469	58.058	31.364	32.019	32.822	40.010	9.944	30.759	30.683
10-HR	MSE	4.022	3.048	3.780	2.157	2.259	2.353	2.360	4.385	3.224	3.215
100-HR	MSE	183.37	109.93	168.28	93.536	96.538	94.398	94.933	39.844	95.231	95.016

1-HR= 1 hour fuel (0-0.6 cm diameter) MSE= mean square error

10-HR= 10 hours fuel (0.6-2.5 m diameter)

100-HR= 100 hours fuel (2.5-7.5 cm diameter)

estimations when modeling spatial continuity (kriging) for 1-HR and 10-HR fuels. Thus, in these cases at least, one traditional technique was better than the simple kriging possibilities. However, the spatial continuity for 100-HR fuels was enough to increase the precision of estimate.

The spatial resolution of the resulted forest fuels maps was implemented at a "point level," in which fuel loadings are estimated at any point in the area of interest. This was implemented under the raster GIS perspective, with the limitation of the raster resolution (in this case 30 x 30 m). This means that using the strategies illustrated in this paper it is possible to define fuel maps at different scales (Yuan 1994). Furthermore, the spatial variation of fire behavior at small scales (heterogeneous conditions) requires levels of resolution that only can be managed under the cell automata (raster) approach (Liu and Chou 1997). Using the vector approach, such as in the fuel-model concept (Finney 1998), fuels distribution is assumed homogeneous within the entire fuel model area. This approach could be useful: (a) at large-scale levels, but with homogeneous landscapes or (b) at small-scale levels with a fine differentiation and classification of fuel models (Campbell and others 1996). However, the latter has been the major problem of the fuel mapping process (Keane and others 1999).

Since the study area is affected frequently by wildfire, it makes sense that any attempt of a sustainable management considers both fire occurrence and fire effects. This information has its higher usefulness when it is considered under a spatial approach. It is not enough to know that we have different fuel loadings along our managed areas, but it is essential it define their spatial variability. The definition of continuous surfaces is a great alternative to understand better the gradual changes of forest fuels. Based on this it will be possible to prioritize which areas have more risk of fire (related mainly in 1-HR distribution), and which areas could produce higher negative effect of the forest ecosystem elements (tree, grasses, soil, water, etc.). The latter is focused mainly on the potential of fire intensity fire, which is related to large dimensions fuels (Albini 1976). Nevertheless, in Mexico this kind of spatial information is not considered, and most of the forest management plans mention the implementation some practical activities as the solution to the fire problem. However, there is not a clear support not only on the implementation of such practices, but in their location and dimension. The methodology illustrated in this paper, could be used to: i) prioritize areas; ii) give dimension to the problem (calculating a given area; and iii) calculate time and cost requirements. Finally, decision makers should consider other ancillary data, such as climate, roads, altitude, wind, vegetation, and human activities. Thinking on fire as a factor that can alter considerably any sustainable management plan, it is

important to spend some time and resources to develop the type of maps showed in this paper.

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