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The efficiency analysis of the fire control operations using the VISUAL-SEVEIF tool.

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Abstract
The suppression costs represent a significant proportion of the total budget available for forest fire protection programs. The need to make efficient use of available budgets requires directing funding towards areas with the lowest costs and maximum benefits. Accordingly, incorporating econometric tools enables establishing criteria to optimize budg*et al*location. Modelling the fire suppression process and budg*et al*location requires knowing how suppression is managed, how resources are dispatched and how costs are incurred.
The methodological approach presented here allows forecasting fire suppression operations productivity, based on suppression difficulty and cost, as well as records from documented fire suppression operation plans from prior fires. On the other side, the value of natural forest resources and the damage and losses from forest fires assessing, help to determining the change net value to estimate the economics fire impacts. For the efficiency analysis of the fire program, is possible using the VISUAL-SEVEIF (Spanish acronym for System for the Economic Evaluation of Wildfires) software tool, to obtain the knowledge of fire behavior and its direct effect on the depreciation of natural resources value, providing the total costs of the losses in the area affected by the wildfire, and the value of the losses for each of the resources identified within the fire perimeter.
This tool work showing both in real time, simulating the spatial development of ground and canopy fires, and the economic losses. The spatial resolution of work will be conditioned by quality and accuracy of fuel model mapping, as well as the characteristics of the digital terrain model, so that in high-precision models the results of the fire behavior dynamic can be up to a square meter. The information layers required by the tool includes one that incorporates the characterization of the natural resources that exist in the area being analyzed and allows determining the economic value of these resources. The import and export possibilities of geo-referenced perimeters, in both vector and raster formats, allows easy transfer of the information generated to geographic information systems (GIS). VISUAL-SEVEIF enables carrying out diagnostic studies of an area that are aimed at the prevention and strategic management of wildfire defense. This paper showing how using this methodology, is possible obtained the efficiency rate of fire suppression activities.

Keywords: *Strategic management, fire prevention, natural resources, GIS, environmental, fire economics, econometrics, fire management, fire program planning, operational plans, fire budgets*

1. Introduction

Forest fires are one of the biggest environmental problems facing the world today, generating significant consequences with regard to both damage and deterioration of forest landscape and its depreciation and economic and social valuation. The abandonment of forest settings, as areas inhabited and affected by humans in terms of actions related to subsistence and energy use, has generated an increase in the accumulation of high-energy biomass over the past few decades (Rodríguez y Silva and Molina 2010, Vélez 2009). This circumstance, coupled with worsening climatic conditions (Piñol *et al*. 1998), has caused a rise in the potential energy released by fire and consequently the virulence of forest fires, resulting in an increase in fire damage to natural resources and the surrounding environment.
The need for strategic information, in relation to the dynamic, energy and expansive potential of fire runs, led to the development of both analytical and graphical simulators. Increased knowledge in fire

science has allowed addressing prediction and simulation studies, thus facilitating their application in wildfire defense activities.

Today's technology provides appropriate prediction and simulation tools that allow effectively developing attack plans in which the priority focus is on safety; it can thus be concluded that prediction and simulation are an ongoing need in protecting forest areas from fire. Moreover, the prediction and simulation exercise allows reducing the time required to achieve control, while facilitating cost savings by providing critical information for the efficient distribution of firefighting resources.

While there has been significant progress in the quality and accuracy of fire behavior forecasts over recent years, important uncertainties remain to be resolved in relation to the simulation of complex phenomena such as energy feedback, the effect of turbulence on acceleration, and the transition and spread of ground fire to the forest canopy. Regardless of future advances in our understanding of fire's dynamic behavior, there is another important need in forest fire management, which is quantifying it in monetary and therefore budgetary terms. Indeed, it is indisputable that any application of a wildfire defense management model is inextricably linked to budget availability and therefore the establishment of priority-based criteria to determine investment levels to implement the management model.

This discussion highlights the importance of studies, research and developments that enable applying econometric criteria to decision-making. Currently, new tools are available, such as the SINAMI econometric model, which allow analyzing in the context of the area and as a matter of strategic planning the most efficient budg*et al*location, by taking into account: the historical background in the frequency and distribution of fires, fire behavior conditions, the economic value of natural resources and the operational capabilities of the firefighting resources (Rodríguez y Silva *et al*. 2010). As discussed by Thompson and Calkin (2011) uncertainty is a major component to consider in developing decision support methodologies "… to facilitate cost-effective, risk-based wildfire planning efforts (p. 1895)." However, the availability of this model and of its ECONOSINAMI software (Rodríguez y Silva 2009, Rodríguez y Silva and González-Cabán 2010) does not resolve in an integrated manner the expansive simulation of fire behavior and the economic evaluation of damages that the simulated fire can potentially generate. This paper presents the structure and operational flow line of the first simulation tool that incorporates the assessment of economic losses caused by fire based on the linear intensity level that the fire develops (kW/m) by each pixel of spatial resolution with which the simulation is performed.

The VISUAL-SEVEIF model (Rodríguez y Silva *et al*. 2013) has been determined by performing the integration in the VISUAL-CARDIN program (Rodríguez y Silva 1999, Rodríguez y Silva *et al*. 2010) of the set of algorithms for the SEVEIF model (Molina *et al*. 2008, Rodríguez y Silva and others 2007, 2010), which were developed for determining and assessing the impact of fire on natural resources in terms of intensity levels released by fire spread. This model offers real-time economic evaluation of losses from post-fire depreciation of natural resources affected.

Valuations of natural resources tend to underestimate the real value of a forest (Constanza *et al*. 1997). Unlike traditional economic activity, the forest environment is characterized by the extraordinary importance of externalities that entail damages or benefits to others of considerable magnitude. From the socio- economic standpoint, all the natural resources must be expressed in monetary terms. The valuation of damages caused by forest fires requires individualized study of each of the resources (tangible and intangible) and their change in net value in relation to fire severity and ecosystem resilience (Molina *et al*. 2009).

The recognition and valuation of natural resources is essential for spatiotemporal planning of preventive work and post-fire rehabilitation (Molina, 2008). Incorporating the concept of vulnerability extends the study beyond the sphere of traditional economic valuation work, integrating two concepts, on the one hand the value of the resource and on the other fire behavior. The integration of the two concepts is performed using a matrix of depreciation rates based on flame length, called a "depreciation matrix" (Molina *et al*. 2011, Rodríguez y Silva *et al*. 2012).

The socio-economic vulnerability model was made through the configuration of a mathematical algorithm associated with a geographic information system (GIS), facilitating the development of spatiotemporal tracking cartography, both at the individual resource level and at the ecosystem's integral vulnerability level. The automation of the calculation and management through GIS is being conducted under the INFOCOPAS project (RTA2009-00153-C03-03) funded by the National Institute for Agricultural Research (INIA), in order to attain versatile geo-referenced knowledge in almost real-time of forest system vulnerability to forest fires.

2. Architecture of simulator

The process followed in the definition and development of the operational architecture of the VISUAL-SEVEIF program consisted of the following phases:

- Review of the VISUAL-CARDIN simulator's software structure in order to locate the assembly position of the economic evaluation module in the program's flow line.
- Selection of natural resources for which losses are to be evaluated based on energy intensity levels that simulated fires can develop.
- Programming of economic evaluation algorithms through C++ computer language.
- Development of interactive windows between the VISUAL-SEVEIF program and the user.
- Determination of input variables, which must be entered in order to perform the calculations.
- Implementation of economic evaluation options included in the VISUAL- SEVEIF program:
  1. Calculation of the monetary value of natural resources located within an area or region (area included inside a polygon, both rectilinear and curvilinear). This option allows determining the economic value of the stocks.
- Calculation of the economic losses and depreciation in the economic value of resources as a result of fire spread. In this phase the procedure followed in the SEVEIF model (Rodríguez y Silva *et al*. 2010) is applied by using the "matrix of economic depreciation factors."
- Assignment of the table of values for the different parameters included in the economic evaluation algorithms, in relation to the types of fuel models.
- Design and final construction of the windows for entering data, performing calculations and showing results. Validation of results with valuations available in the database of recorded fires.

2.1. VISUAL-CARDIN component

Technological developments in the field of computer science have enabled the development of simulation software of great versatility and usability, offering many tool options that are of great help in decision-making. In this regard, forest fire protection requires specialized programs that provide information on forecasts of dynamic fire behavior associated with fires that evolve in different forest systems. In this sense, the VISUAL-CARDIN program is structured as a deterministic program that works subject to the following conditions:

Simulation model through cellular automaton using the more nearest neighbor

Considerations:

1. Terrain topography.
2. Fuel model in each pixel (cell).
3. Tree height, crown base height, and crown density.
4. Fuel moisture and degree of protection.
5. Wind direction and intensity.
6. Ambient temperature and humidity.

The speed (V) and direction of maximum spread at each point is calculated from the following expression:

$V=(V_0 + V_i \cdot \cos W)\cdot t$ (1)

Where Vo is the rate of spread with zero wind and slope, Vi is the increase in speed in the direction of maximum spread due to the combined effects of wind and slope, φ is the spread radius from the origin of the fire, W represents the angle formed with the maximum spread direction Vi>Vo,
The geometric figure adopted to model the surface expansion of the fire's figure is a cardioid. The excess width on the elliptical reference figure is corrected by a factor (perpendicular to maximum spread). This factor is the ratio between the maximum width provided by the simulation performed by Behave (Andrews 1986) and the maximum width of the theoretical figure produced by the geometry of the cardioid. The maximum width value is determined by the expression (Martínez- Millán 1990, Martínez-Millán *et al*. 1991, Caballero *et al*.1994):

$F= (3V_0 + (V_0^2 + 8Vi^2)^{0,5}) (4V_i^2 - 2V_0^2 - V_0 (V_0^2 + 8V_i^2) / 16V_i^2$ (2)

The input parameters required by the program for the simulation are entered via the module parameters, which allows including data associated with local characteristics through a set of commands. Through the winds command, the characteristics of wind speed and direction measured at six meters above the ground can be entered. The moisture command offers the ability to assign the moisture of both living and dead fuels, with the latter classified according to their geometric characteristics. Alternatively, dead fine fuel moisture can be obtained from a set of calculations based on data such as the date, effects of weather, terrain and vegetative state. The protection command allows assigning the fuel's degree of protection of against wind, whereas the residence command option establishes the flame and ember residence times, allowing assignations to each of the different fuel models. Adjustment of input data using this command allows simulation of the phenomenon of revival from increases in wind speeds. In the simulation, there are some scenarios in which the conditions of transition from a ground to tree-stand crown fire produce a shift in combustion towards the canopy and therefore the fire spreads through the treetops. That is, the model recognizes the possibilities and if conditions allow it, ground, mixed and crown spread are produced. This feature certainly offers great versatility and accuracy in determining the economic impact of fire, by being able to capture the strong energy increases associated with forest canopy spread and thus be able to relate it to damages and losses generated.
Conducting post-fire analysis, in order to reconstruct the behavior of the fire and corroborate the results obtained by the different attack plans applied to extinguish it, is another feature offered by the simulator. This option allows qualifying the final fire reports while at the same time evaluating the performance of the various resources deployed. In this same option, the possible application of educational and technical training courses in fire suppression and behavior can be incorporated.
From the simulation outcomes, a database can be built that interrelates the affected area simulated in freely-evolving, spread dynamics, i.e. without the inclusion of firefighting actions, and the actual final area obtained after extinguishing the fire. The ratio between the two areas determines the spread rate control. This parameter facilitates the development of information bases on the experiences recorded in attack plans developed and implemented. This allows having a query file on those fires that may occur in the future and evolve under similar environmental conditions.
From this historical knowledge, firefighting simulations can be initiated on the set of resources that must be activated to control and extinguish the forest fire. To the extent that the integration of economic evaluation algorithms in the VISUAL- CARDIN software architecture has enabled the calculation of economic losses, the VISUAL-SEVEIF model opens a window to the possibility of making calculations and relationships that link firefighting operations and their costs with the value of the natural resources and the economic losses resulting from fire spread. Efficiency studies on the

results of firefighting operations will help in defining budget options and the best results in wildfire defense planning.
The current version responds to programming in C++ under the Windows operating system, but it will also soon be available for the Linux operating system, and includes significant improvements in pixel-by-pixel information processing, providing more precise information with regard to spread characteristics (rate of spread, linear intensity of the advancing front and flame length).
The graphical environment has also been taken into account in order to facilitate greater mapping options, as the simulation can be performed on raster coverages of the topographic map at different scales. It allows export of the perimeters in raster and vector format, as well as import of fire or area perimeters, measured with GPS and also in vector format. Shown below is the results window, which includes the area covered by the fire in yellow (Figure 1).

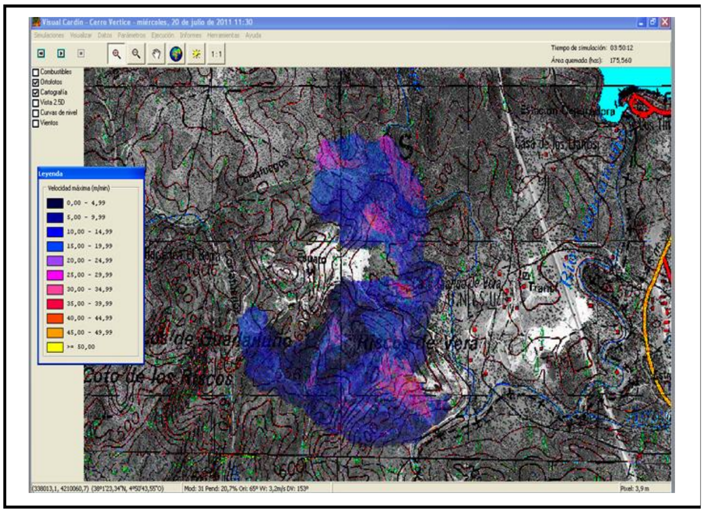

Figure 1—Simulation and analysis of fire behavior using VISUAL-CARDIN software for the Vertice Hill wildfire, 03h:50m after ignition (2011. Cordoba, Spain).

3. Economic valuation of natural resources: SEVEIF Model

In the first version of the VISUAL-SEVEIF simulator, we have incorporated the most important algorithms corresponding to the natural resources that have high representativeness in forest scenarios and that with the development of the SEVEIF model (Rodríguez y Silva *et al*., 2010) were identified as such.
The natural resources considered for economic valuation are the following: tangible resources, environmental services and landscape assets. The valuation of tangible resources including timber and non-timber products. The methodological approach for valuation of the impact on the timber resource is based on an algorithm that integrates the valuation tools, which include trees of both natural and artificial origin (Rodríguez y Silva *et al*. 2012). The valuation of non-timber resources is based on expressions used in the Manual for the Valuation of Losses and Estimation of Environmental Impact by Wildfires (Martínez Ruíz 2000). The evaluation of the impact on the hunting resource is carried out through the adjustment proposed in Zamora and others 2010.
The valuation of environmental services includes three resources: carbon fixation, erosion control and faunal biodiversity. The valuation of carbon fixation includes both the amount fixed at the time of the fire's occurrence and the amount unfixed from that time on, with prior knowledge of bark, aerial biomass and annual increment volumes being necessary (Table 1). The amount of carbon corresponding to the dry biomass is estimated at 50%. Erosion control will be expressed in economic income loss based on the potential amount of soil lost per unit area. The expression used for the

valuation (Table 1) incorporates a sum in relation to losses incurred during the first rains (bare soil) and a second sum that includes progressive soil losses until recovery of vegetation with similar burn protection (Molina and others 2009). Valuation of faunal biodiversity or unique species is performed using the cost of species recovery programs, or if no specific program is available through the contingent valuation method (Molina 2008).

Resource	Algorithms	Source
Timber	$V_{tim} = (1,7*E*B)/(E+0,85*B)$ $E = C_0*p\ [i^e + g(i^e -1)] + A*(i^e – 1)$ $E = (C_{0/z}*t\ [i^e + g(i^e -1)] + (C_0/z)*0,5*(i^e - 1)$ $E = [P*V -P *V] + P*V\ [(i^{(T-e)} - 1)/(i^{(T-e)})]$ $B = [(V*P*1,025)/1,04]*[1- (1,025/1,04)^e]*[1 + X*h*p]$ $B = V*h*t[R*P + (1 - R)*P_1]$	Rodríguez y Silva *et al*. 2012
Firewood us	$V_{firewood} = P_x*R_x*[((1+i)^n - 1)/(i*(1+i)^n]$	Molina *et al*. 2011
Hunting	$V_{hun} = P_x*R_x*[(1+i)^n - 1)/(i*(1+i)^n] + S$	Zamora at al. 2010
Carbon fixation	$V_{carb} = CF*PM + IF*PM*RC*[((1+i)^{T-e} – 1)/(i*(1+i)^{T-e}]$	Molina. 2008
Erosion control	$V_{eros} = R_1*P_1 + R_2*P_2\ [((1+i)^n – 1)/(i(1+i)^n)]$	Molina *et al*. 2009
biodiversity; Landscape; recreation; Unused	$V= Rx*[((1+i)^n - 1)/(i*(1+i)^n]$	Molina. 2008

Table 1. List of the algorithms included in the VISUAL-SEVEIF software, for each different resources considered

where E is the timber valuation based on the traditional Spanish approach (€/ha), B is the timber valuation adapted from the American Model (€/ha), Co is the cost of replanting one hectare of land (€/ha), p is the percentage of the stand affected by fire, i is the annual interest rate, g is annuity dependent on the rotation of the species, A is the value of a hectare of land without trees (€/ha), e is the estimated age of the stand at the time of the fire, V is the timber volume expressed in m^3/ha, P is the m^3 price of felled wood (€), n is the number of years remaining until the hypothetical harvesting rotation, X is the mortality rate dependent on the severity of the flames, h is the percentage of the species in the canopy, z is the reduction in replanting cost due to the self-regenerative phenomenon based on the rotation, P1 is the price of damaged wood with commercial use (€/m^3), V1 is the volume of damaged wood with use (m^3/ha), Px is the price per unit of measurement of the resource (€), Rx is the annual income per unit area, S is the reproductive stock per unit area (€), CF is the amount of CO_2 retained at the time of the fire (t/ha), PM is the price per fixed ton (€/t) , IF is the annual increase in CO_2 retained (t/ha), RC is the income generated by fixing a ton of carbon in a year (€), R_1 is the average amount of soil lost the first year (t/ha), P1 is the estimated price per ton (€), R_2 is the average amount of soil lost until recovery of the original cover (t/ha).

4. **Spatial identification of different damage levels and net change in the value of resources**

Determining losses in natural resources, both tangible and intangible, requires knowing the remaining value of the resources, i.e., the "net change in the value of the resources." This concept requires the incorporation of resource depreciation based on fire intensity level. Assigning the depreciation of each resource based on fire intensity level is made on the basis of depreciation rates or percentage levels, given their greater simplicity and practical applicability.

In the case of the timber and firewood use resources, and under the framework of the FIREMAP, SINAMI and INFOCOPAS research projects, circular plots with a 10-m radius were taken for different plant typologies and degrees of damage in the following fires: Huetor (1993), Aznacollar (1995), Estepona (1995), Los Barrios (1997), Cazorla (2001, 2005), Aldeaquemada (2004), Minas de Ríotinto (2004), Alajar (2006), Gaucin (2006), Obejo (2007), Orcera (2009) and Vértice Hill (2011). For the valuation of losses incurred by the hunting resource, information from Montfrague National Park and the Aldeaquemada and Minas de Ríotinto fires (Zamora *et al*. 2010) was used in order to have not only spatial but also temporal analysis of the natural recovery of reproductive stock and, consequently, of the annual income generated by the hunting resource.

Depreciation levels of the carbon fixation and erosion control resources were estimated based on tree mortality and the consumption level of aerial biomass, from measurements of burned and unburned trees with similar dendrometric characteristics (fires of: Monte Catena, 2009, Obejo 2007, Cazorla 2001, 2005). Economic valuation of erosion damage, or conversion of lost biomass into monetary units, was determined based on the Obejo fire (2007) study, which analyzed the costs associated with the loss of different soil amounts (tons per hectare). In the case of biodiversity, damage valuation is based on the "surrogate value" applied by the Administration (recovery and/or conservation programs) or the value given by the population (contingent valuation methodology). The values obtained for this resource include adjustments based on post-fire costs incurred by the pertinent authorities to prevent the escape and migration of species through the application of food supplementation, predator elimination and competition reduction measures (Molina 2008).

The depreciation rates of landscape assets are very difficult to validate. The aforementioned research projects estimate the depreciation rates for these assets by the technique of social preferences or valuation through indirect landscape perception techniques by pre-fire and post-fire comparison of a territory. Landscape use is affected to a greater extent than leisure and recreational activities. Large wildfires that occurred in Sierras de Cazorla, Segura y Las Villas Natural Park (place where the Catena Hill fires occurred in 2001, 2005 and 2009) provided a good database for quantitative estimates on the impact on landscape assets. It can thus be stated that the 2005 fire resulted in a 40% decrease in the number of tourists and paralyzed numerous business projects for remodeling and expanding recreational facilities. Use of Geographic Information Systems (GIS) allows identification of plant typology and its economic valuation, as well as the availability of information about fire behavior. Based on this, the depreciation rate for each resource is estimated individually. The integration of the two concepts provides the economic vulnerability of each resource present in the burned area. The economic valuation of damages is the sum of the vulnerabilities of the resources present in the burned area.

5. Classification of fire intensity level from average flame length

Determining the effects of potential fire behavior on the economic valuation of stocks has bee done by identifying the average flame length for each pixel (directly related to the linear intensity of the advancing front). That information is obtained directly from the results provided by the VISUAL-CARDIN program in each of the pixels covered by fire spread. Four fire intensity levels were identified:

Degree of damage I. It corresponds to Fire Intensity Level (FIL) VI or flame length greater than 12 m. Area severely affected. Continuous crown fire is the most representative for this degree.

Degree of damage II. It corresponds to Fire Intensity Level (FIL) V and IV or flame length between 9-12 m and 6-9 m. Moderate affect. Passive crown fire with some crown runs. The ground is left unprotected by clumps due to the intensity. There is almost total surface fuel consumption.

Degree of damage III. It corresponds to Fire Intensity Level (FIL) III or flame length between 3-6 m. Area moderately affected. Ground fire with consumption of surface material. The fire advances with the slope but not the wind. There are isolated scorched trees.

Degree of damage IV. It corresponds to Fire Intensity Level (FIL) II or flame length between 2-3 m. Area slightly affected. Ground fire with consumption of surface material. The fire moves backwards, without slope or wind in its favor.

6. **Identification of net change in the value of the resources and the VISUAL-SEVEIF software flow line**

From the experience gained in the large wildfires that occurred in Andalusia during the period 1993-2011 and the scientific results of the FIREMAP, SINAMI and INFOCOPAS research projects, the depreciation matrix was made (Rodríguez y Silva *et al*. 2009), (Figure 2). This matrix is made up of the set of percentage factors based on the fire intensity levels (kW/m) and the corresponding degree of damage, as indicated in the previous section, so that when applied to the initial socio-economic value, it provides both the losses caused by the wildfire and the residual economic value of vegetation unaffected by the fire.

NIF	Vtr	Vfwr	Vhr	Vcar	Verr	Vbir	Vlar	Vler	Vnonr
I	8,33%	5%	20%	10%	10%	20%	5%	2%	4%
II	16,65%	10%	45%	25%	25%	40%	25%	20%	19%
III	38,58%	20%	65%	45%	45%	60%	60%	55%	46%
IV	57,85%	45%	85%	65%	65%	80%	80%	65%	54%
V	82,79%	65%	95%	85%	85%	100%	90%	85%	69%
VI	89,41%	75%	100%	100%	100%	100%	100%	85%	69%

Figure 2—Depreciation matrix ("Vtr", timber resource depreciation (Rodríguez y Silva and others 2012); "Vfwr", firewood use depreciation; "Vhr", hunting resource depreciation; "Vcar"; carbon resource depreciation; "Verr", depreciation of erosion control; "Vbir", depreciation of faunal biodiversity; "Vlar", depreciation of landscape resource; "Vler", depreciation of leisure and recreation resource; "Vnonr", depreciation of non-use resource).

In the VISUAL-SEVEIF software architecture, the depreciation matrix has been integrated in order to provide automatically, and for each pixel concerned, the percentage reduction in the initial economic value as a result of the fire behavior developed in it. The VISUAL-SEVEIF software flow line has been defined by the following sequence of calculation processes (Figure 3):

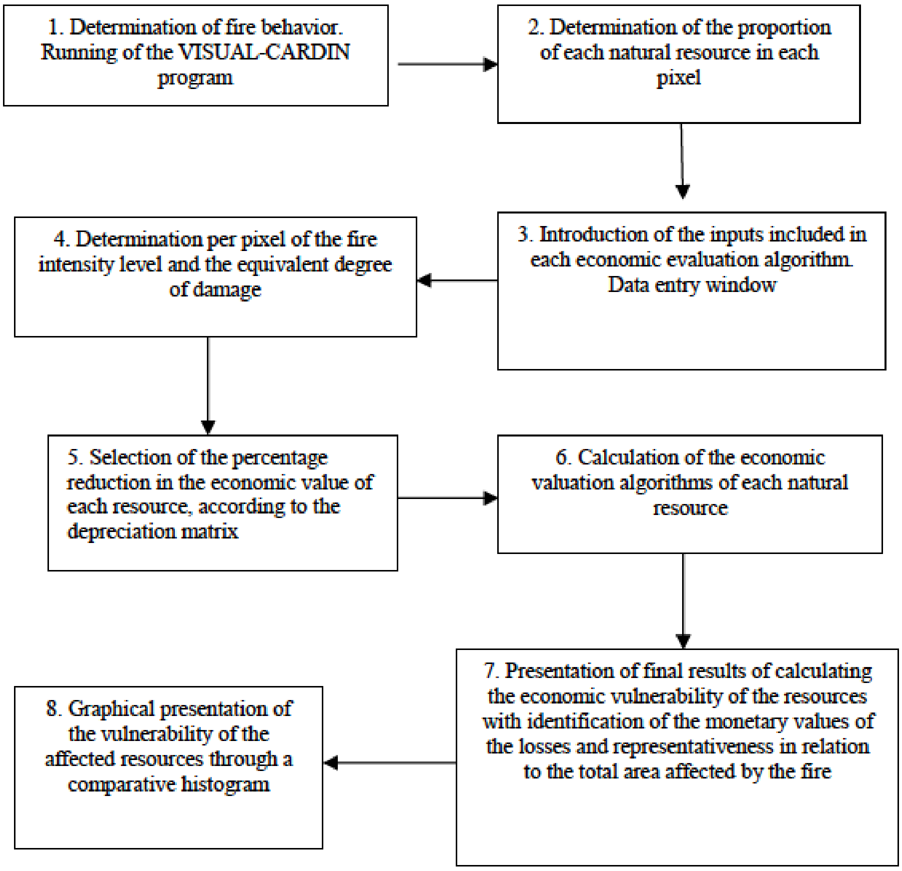

Figure 3—Flow line of the operational process corresponding to the VISUALSEVEIF computer program.

The final windows of the VISUAL-SEVEIF software shown the both report, fire behaviour shape and economic losses affected by different resources (Figure 4).

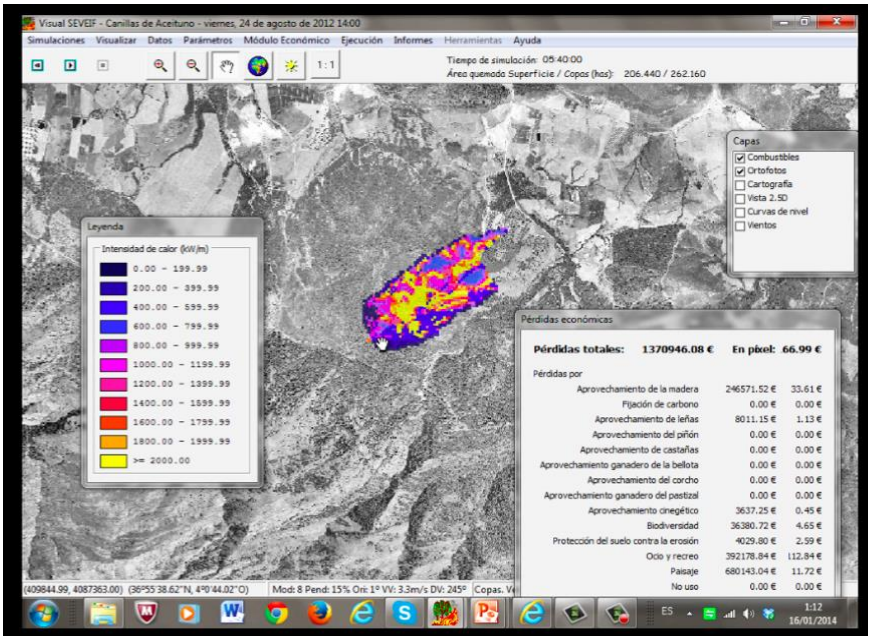

Figure 4. Window of VISUAL-SEVEIF software, showing the fire shape with fire intensity (kw/m) and the economic losses by the resources affected for the fire propagation

7. Estimation of the efficiency of suppression methods using economic losses in natural resources and suppression cost relationship.

Determining the efficiency of production systems, can be understood as an econometric technique through which the existing relationship between the resources employed or assigned and the results obtained, or the target previously set as a goal to be reached, is addressed. That is, it can be understood as the relationship between revenues and expenditures or inputs and outputs generated in a given production system. Conceptually and when evaluating suppression operations, efficiency can be associated with estimating a ratio that allows getting information from the results obtained from using a particular set of suppression resources and their incurred costs on a specific incident or fire (Mendes, 2010).

The efficiency isoquant curve is estimated using data from the fire occurrence database in the forest region or district in which the efficiency analysis is performed. Once the econometric components of the efficiency and its conceptual identification have been achieved the analysis and study of the results of forest fire control and suppression operations can proceed. Using the analysis method for determining efficiency based on econometric model applied to forest fire suppression operations, if necessary to identify for each fire the relationships between the input and the output (Rodríguez y Silva and Gonzalez-Caban. 2013). Inputs refer to the economic value of the area that has been successfully protected based on suppression activities defined when planning the suppression operations. The inputs represents (total economic value saved from the impact of the fire within the fire perimeter), Vr is the economic value of each of the resources in the area where the wildfire has evolved (area bounded by the final fire perimeter), expressed in monetary units (€, $), and Fd is the depreciation factor of the economic value due to the effect or impact of the fire (Molina *et al*. 2009, Rodríguez y Silva and González Cabán 2010, Rodríguez y Silva *et al* 2012). The inputs is obtained using the VISUAL-SEVEIF software.

The outputs or suppression costs are the sum of the individual costs of all suppression resources dispatched to the fire (Ce_j). In terms of efficiency analysis, outputs are the resulting solutions from the combination of suppression resources with a production rate level allocated to the economic value of the resources at risk saved from the impact of the fire. This is the output or suppression costs of the operational suppression system. Accordingly, the efficiency expression can be written as follows, where ET is the efficiency estimator, and all other variables as previously defined (Rodríguez y Silva and Gonzalez-Caban. 2013):

$$ET = 1 - \left[\sum_{j-1}^{j-m} Ce_j / \sum_{i-1}^{i=n} Vr_i \,(1 - Fd_i)\right]$$

From last equation ET values result from the ratio between revenues (outputs) and expenditures (inputs); therefore, it can generalize that:

If $0<ET<1$, then the efficiency is low to very high
If $ET=1$, then the efficiency is in balance

To establish measurement consistency, adjustments are necessary to the ET equation. To do this, weights are introduced that normalize the measurement heterogeneity among the variables in the equation. The weights help put all variables in terms of the ratio of its value to the total overall value for that variable. Thus, for the case of the different suppression resources used (outputs), the weights (β_j) represent the time each resource was used in relation to the total elapsed time from the start of suppression actions until the fire is under control. For the inputs or economic value of each natural resource, the weights (α_i) represents the economic value of each resource relative to the total economic value of all natural resources in the area affected by the fire. By applying the weighting criteria to ET, we obtain the following equation:

$$ET = 1 - \sum_{j=1}^{j=m} \beta_j (Ce_j) / \sum_{i=1}^{i=n} \alpha_i Vr_i (1 - Fd_i)$$

For simplicity, we suggest a somewhat arbitrary qualitative classification of the results to establish an efficiency ranking (Table 1) by associating the ET estimates to four categorical levels: Low, Moderate, High, and Very High.

Efficiency value interval (ET)	Qualitative classification
0<ET<0.26	LOW
0.26≤ET<0.6	MODERATE
0.6≤ET<0.7	HIGH
0.7≤ET<1	VERY HIGH

8. **Conclusions.**

The recognition or valuation of forest ecosystems is essential for the spatiotemporal planning work of forest fire managers. The importance of having an evaluation model of socio-economic impacts encompasses a wide range of possibilities, facilitating prevention, valuation and post-fire restoration work. Finally, the methodological approach presented here provides options for the combined study of suppression costs and residual economic valuation of natural resources after the impact of a forest fire. For example, the information produced permit managers not only to analyze and classify the results of agreed upon and applied fire suppression options, but also to make adjustments in the combination of suppression resources assigned if necessary. The VISUAL-SEVEIF software is an objective tool for use in fire economic planning and decision making.

9. **References**

Andrews, P. 1986. Behave: Fire Behavior Prediction and Fuel Modeling System. Burn Subsystem, part 1. USDA Forest Service. Intermountain Research Station Odgen, UT 84401. General Technical reports INT-194.

Borchert, M., Johnson, M., Schreiner, D., Vander Wall, S. 2003. Early postfire seed dispersal, seedling establishment and seedling mortality of *Pins coulteri* (D.Don) in central coastal California, USA. Plant Ecology 168(2), 207-220.

Caballero, D. Martínez-Millán, J., Martos, J., Vignote, S. 1994. Cardin 3.0. A model for forest fire spread and fire fighting simulation. II International Conference on Forest Fire Research. Proceedings. November 1994. Coimbra. Portugal.

Constanza R., D'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, G.R., Sutton, P., Van der Belt, M. 1997. The value of the world's ecosystem services and natural capital. Nature 387: 253- 260.

Martínez Millán, J. 1990. Fire behaviour modelling research and practice. International Conference on Forest Fire Research. Proceedings. November 1990. Coimbra. Portugal.

Martínez Millán, J., Vignote, S., Martos, J., Caballero, D. 1991. Cardín, un sistema para la simulación de la propagación de incendios forestales. Ministerio de Agricultura, pesca y Alimentación. Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria. Investigación Agraria. Sistemas y Recursos Forestales, vol.0-1991- separata no:10. Madrid.

Martínez Ruiz, E. 2000. Manual de Valoración de Montes y Aprovechamientos Forestales. Ediciones Mundi-Prensa, Madrid.

Mendes I. 2010. A theoretical economic model for choosing efficient wildfire suppression strategies. Forest Policy and Economics 12: 323-329.

Molina, J.R. 2008. Integración de herramientas para la modelización preventiva y socioeconómica del paisaje forestal frente a los incendios en relación con el cambio climático. Tesis Doctoral.

Molina, J.R., Rodríguez y Silva, F., Herrera M.A., Zamora, R. 2009. A simulation tool for socio-economic planning on forest fire suppression management. Libro Forest Fires: Detection, Suppression and Prevention. Nova Science Publishers. USA.

Molina, J.R., Herrera, M.A., Zamora, R., Rodríguez y Silva, F., González-Cabán, A. 2011. Economic losses to Iberian Swine production from forest fires. Forest Policy and Economics 13: 614-621.

Piñol, J., Terradas, J., Lloret, F. 1998**.** Climate Warming, Wildfire Hazard, and Wildfire Occurrence in Coastal Eastern Spain. Climatic Change 38(3): 1480-1573.

Rodriguez y Silva, F. 1999. A forest fire simulation tool for economic planning in fire suppression management models: an application of the Arcar-Cardin. Proceedings of the Symposium on Fire Economics, Planning and Policy: Bottom lines, USDA Forest Service. Pacific Southwest Research Station. General Technical Report PSW-GTR- 173. San Diego California**.**

Rodríguez y Silva, F., Molina, J.R., Herrera, M., Zamora, R. 2007. Vulnerabilidad socioeconómica de los espacios forestales frente al impacto de los incendios, aproximación metodológica mediante sistemas de información geográficos (proyecto Firemap). IV International Wildland Fire Conference. Proceedings. Sevilla. (www.wildfire07.es).

Rodríguez y Silva, F., Molina, J.R., Herrera, M.A., Zamora, R. 2009. The impact of fire and the socioeconomic vulnerability of forest ecosystems: A methodological approach using remote sensing and geographical information systems. General Technical Report PSW-GTR-227. Pacific Southwest Research Station. Forest Service, U.S. Department of Agriculture; 151 - 168.

Rodríguez y Silva, F., González-Cabán, A. 2010. "SINAMI": a tool for the economic evaluation of forest fire management programs in Mediterranean ecosystems. International Journal of Wildland Fire 19: 927-936.

Rodríguez y Silva, F., Molina, J.R. 2010. Manual Técnico para la Modelización de la Combustibilidad asociada a los Ecosistemas forestales Mediterráneos. Departamento de Ingeniería Forestal. Universidad de Córdoba. Córdoba. España.

Rodríguez y Silva, F., Molina, J.R., González-Cabán, A.; Herrera, M.A. 2012. Economic vulnerability of timber resources to forest fires. Journal of Environmental Management 100: 16-21.

Rodríguez y Silva, F., Gonzalez-Caban, A. 2013. Forecasting Productivity in Forest Fire Suppression Operations: A Methodological Approach Based on Suppression Difficulty Analysis and Documented Experience. General Technical Report PSW-GTR-245. Pacific Southwest Research Station. Forest Service, U.S. Department of Agriculture; 50 - 65.

Rodríguez y Silva, F., Molina Martínez J. Herrera Machuca M., Rodríguez Leal J. 2013.VISUAL-SEVEIF, a Tool for Integrating Fire Behavior Simulation and Economic Evaluation of the Impact of Wildfires. General Technical Report PSW-GTR-245. Pacific Southwest Research Station. Forest Service, U.S. Department of Agriculture; 163 - 178.

Thompson M, Calkin D**.** 2011. Uncertainty and risk in wildland fire management: A review. Journal of Environmental Management 92: 1895-1909.

Vélez, R. 2009. La Defensa contra incendios forestales. Fundamentos y Experiencias. McGraw-Hill, Madrid.

Zamora, R., Molina, J.R., Herrera, M.A., Rodríguez y Silva, F. 2010. A model for wildfire prevention planning in game resources. Ecological Modeling 221: 19-26.